Beam and near detector

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2/1/2017

The most important near detector parameter is its distance. How is this determined ?

Why is the ND at 574 m from target ?

- ***Reminder of the ND requirements and numerical consequences.***
- ***Current near site layout and driving requirements***
- ***The decision to place the near detector at 574 m was made in 2012 in preparation for CD1. It was influenced by these factors:***
  - ***The beam was placed on the surface using a hill.***
  - ***At that time Muon range out distance was calculated to be 210 m from absorber.***
  - ***The possibility of extending the beam tunnel to 250 m was kept open.***
  - ***The ND/FD ratio was ~(rFD/rND)^2 for an ND site as far away possible, but still within FNAL boundaries.***
  - ***The LBNE exec and project made this decision jointly for CD1 in response to the requirement for ND/FD ratio and the long muon range distance.***

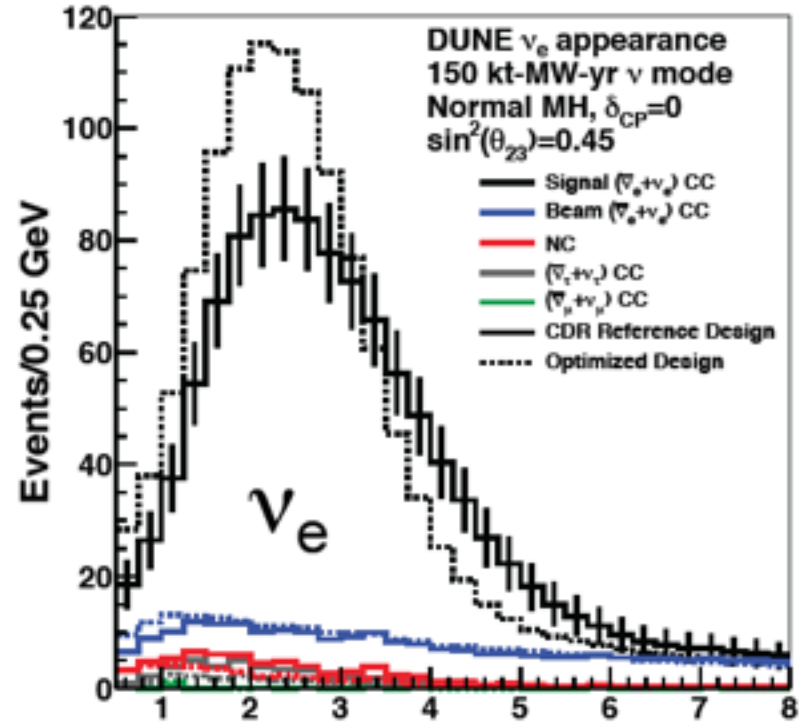
DUNE ND requirements

$Osc.\,freq = (1/500) km/GeV$

$Sampling > 2 \times Osc.freq$

- **The current set of broadly written scientific requirements are in DOCDB-112. This was covered in the CD1(R) and CD3a reviews.**

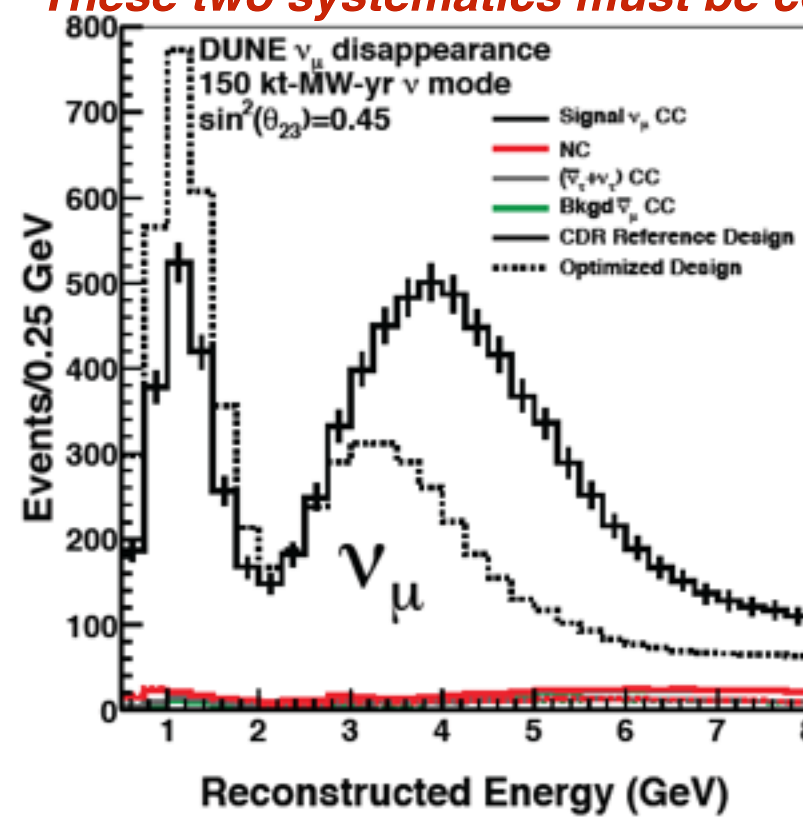
- **The Near Detector Complex measurements shall be sufficiently precise and accurate that the long-baseline neutrino oscillation analysis capability shall be limited by the statistics of the planned exposure and the systematic uncertainties of the far detector.**



bin	electron events	% syst req=stat/2
0-0.8 GeV	60	6%
0.8-1.7 GeV	130	4%
1.7-2.6 GeV	540	2%
2.6-5.2 GeV	380	2.5%
>5.2 GeV	~150	4%

These two systematics must be considered simultaneously.

- **The near neutrino detector shall be placed on axis with the neutrino beam; it shall be placed sufficiently far to satisfy two conditions: all muon flux from the beam should be absorbed before the neutrino beam reaches the near detector, and the uncertainties due to beam spectrum comparison between far and near should be highly constrained.**



bin	muon events	statistical error
0-0.8 GeV	600	4%
0.8-1.7 GeV	2000	2.2%
1.7-2.6 GeV	670	4%
2.6-5.2 GeV	5500	1.3%
>5.2 GeV	~2000	2.2%

It is worth reading the requirements, commenting on them, and looking at how to satisfy them or not. They need to be made numerical with a specific design !

Summary of needed accuracy

- **Given 1300 km, the broad band nu-e event spectrum will need to be measured with energy resolution better than ~0.5 GeV.**

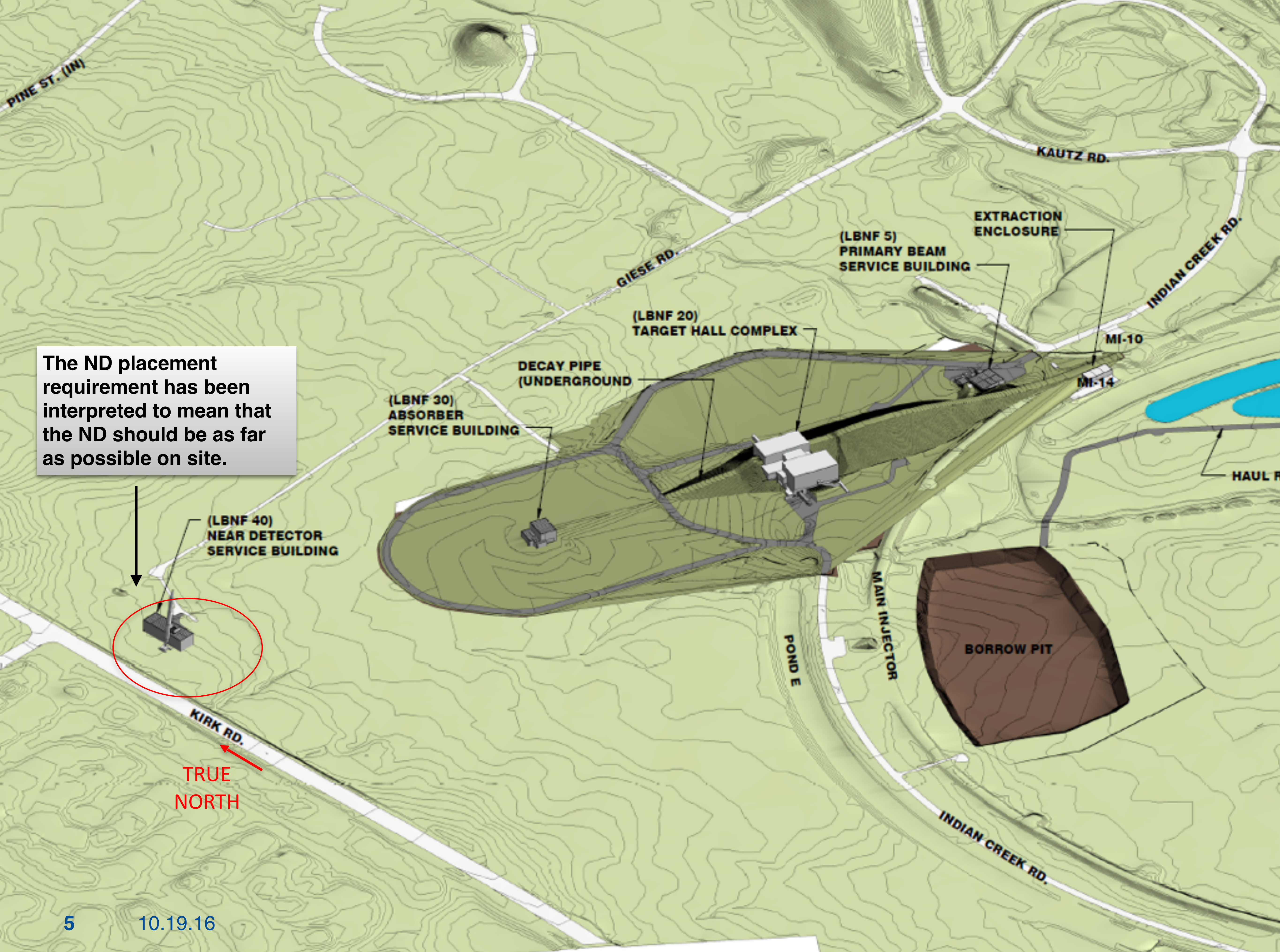
- **The systematic error on the prediction of electron neutrino spectrum should ultimately be ~2-5% per bin. But initially this can be much poorer and will change over time as 1/Sqrt[exposure].**

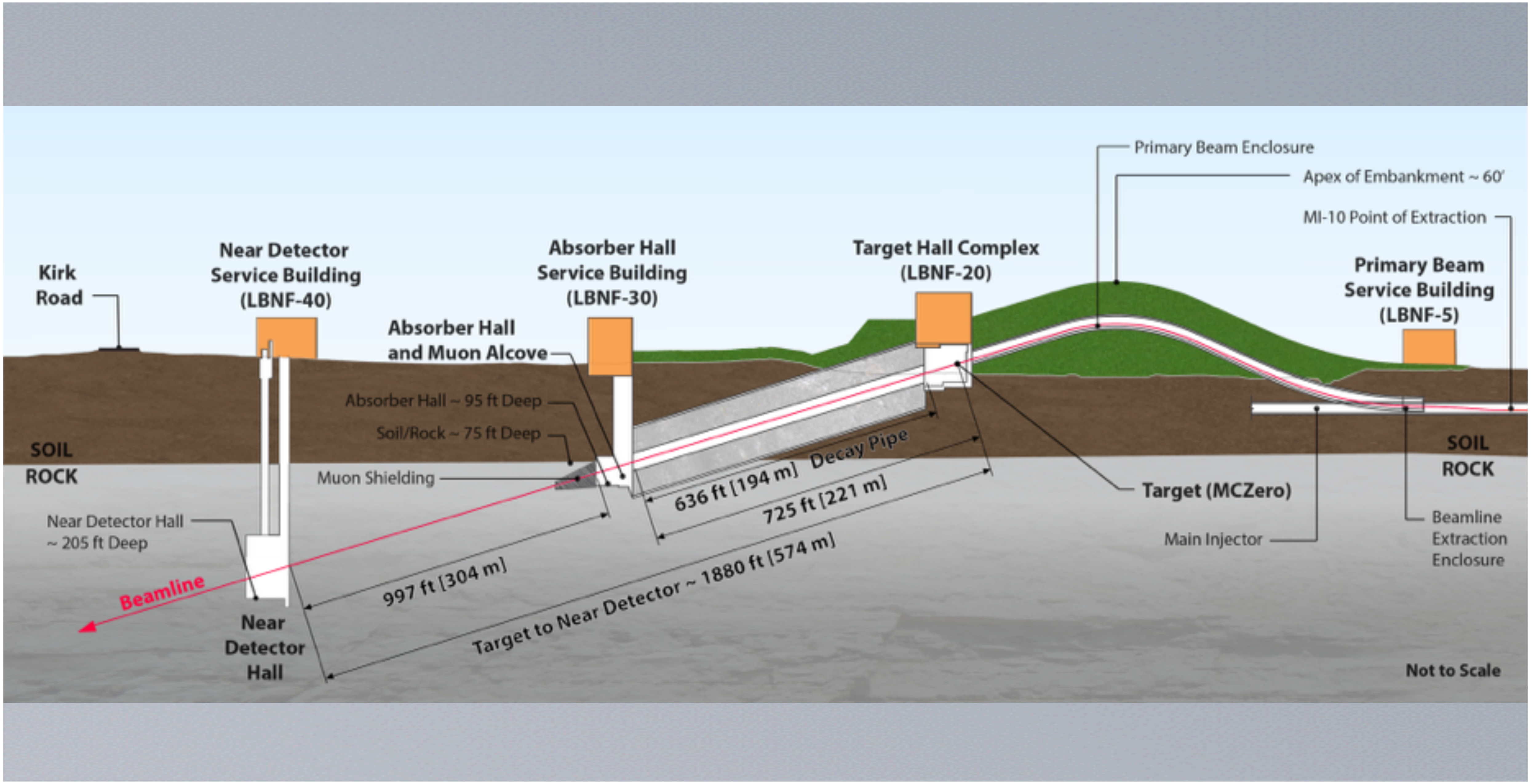
- **The systematical error on the prediction of unoscillated muon neutrino spectrum should be ~2% across all bins.**

- **Muon energy resolution and scale is very important to determine the Delta-m^2, but the shape allows significant reduction in the requirement. The energy resolution is crucial for mixing angle resolution.**

- **Both electron and muon spectra have to be analyzed together to perform the CP fits because they depend on the location of the "node" which depends on Delta-m^2 and so both muon and electron systematic errors have to be achieved simultaneously.**

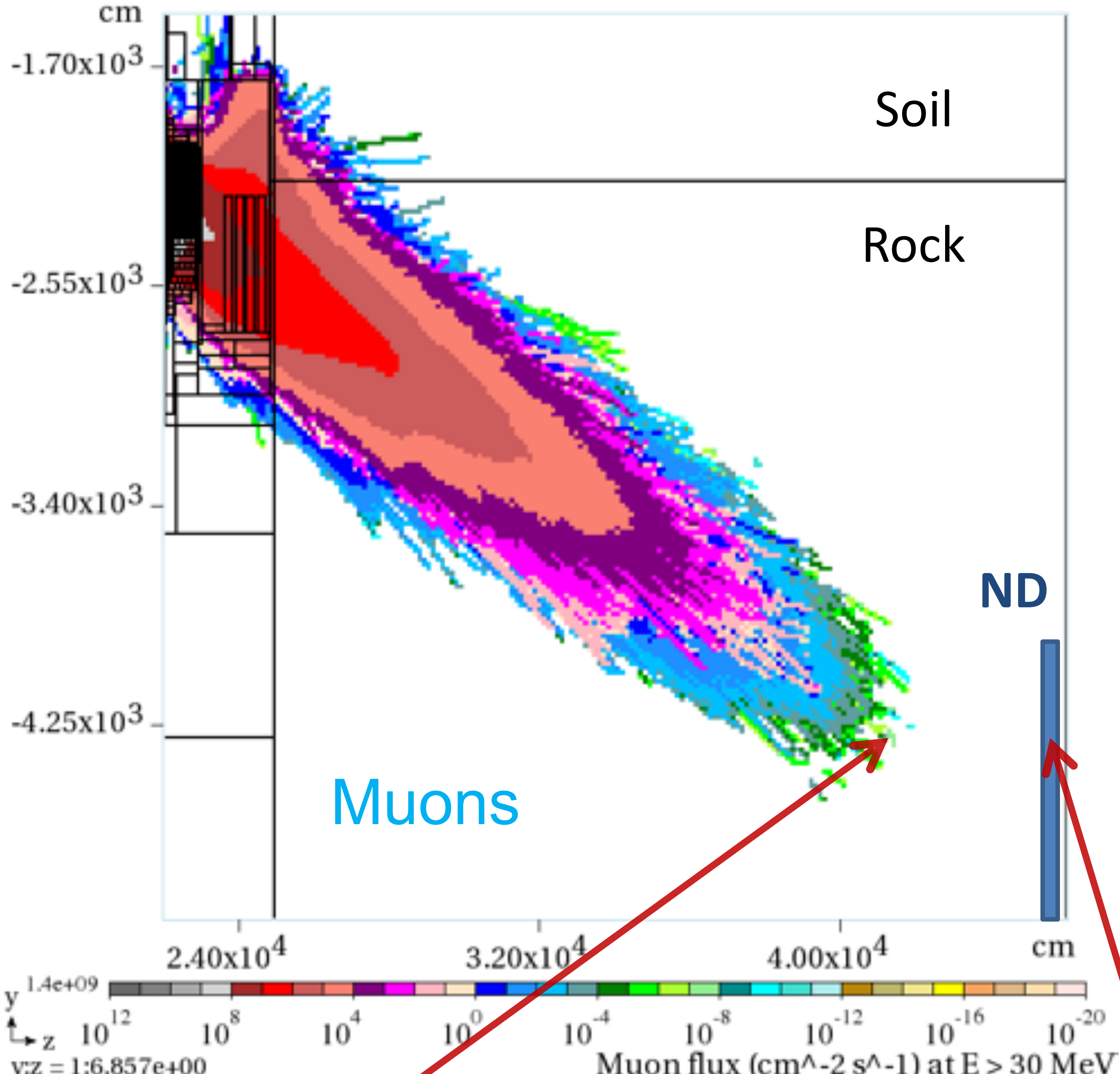
The ND placement requirement has been interpreted to mean that the ND should be as far as possible on site.

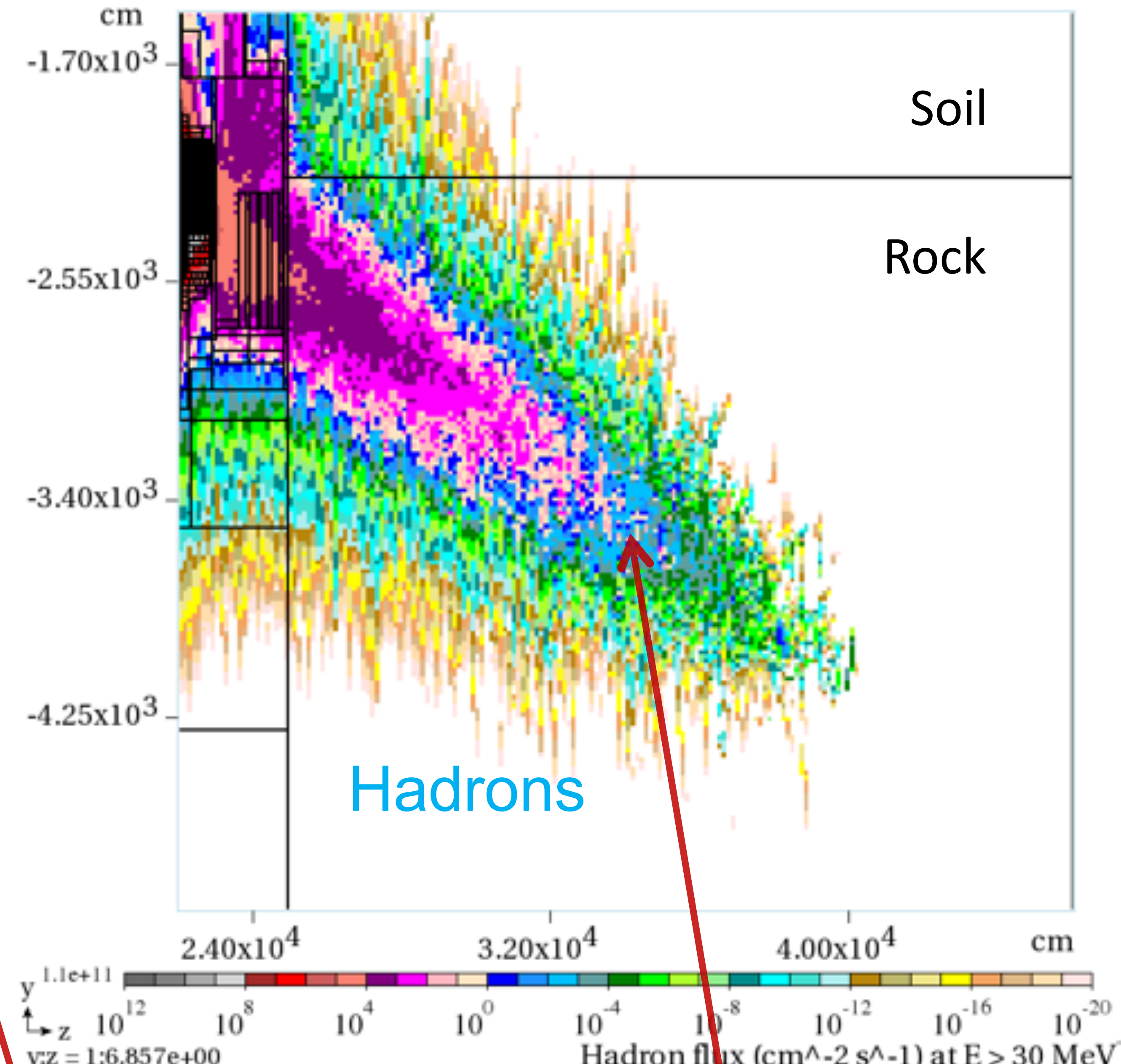




LBNE DocDB 11180: The near detector location is 574 m from the target station based on the requirement that it be placed as far away as possible to obtain the smaller ND/FD flux ratio.

Muon/Hadron Fluxes ($cm^{-2}\ s^{-1}$) Downstream Absorber Hall
Assumption is 120 GeV with 2.4 MW





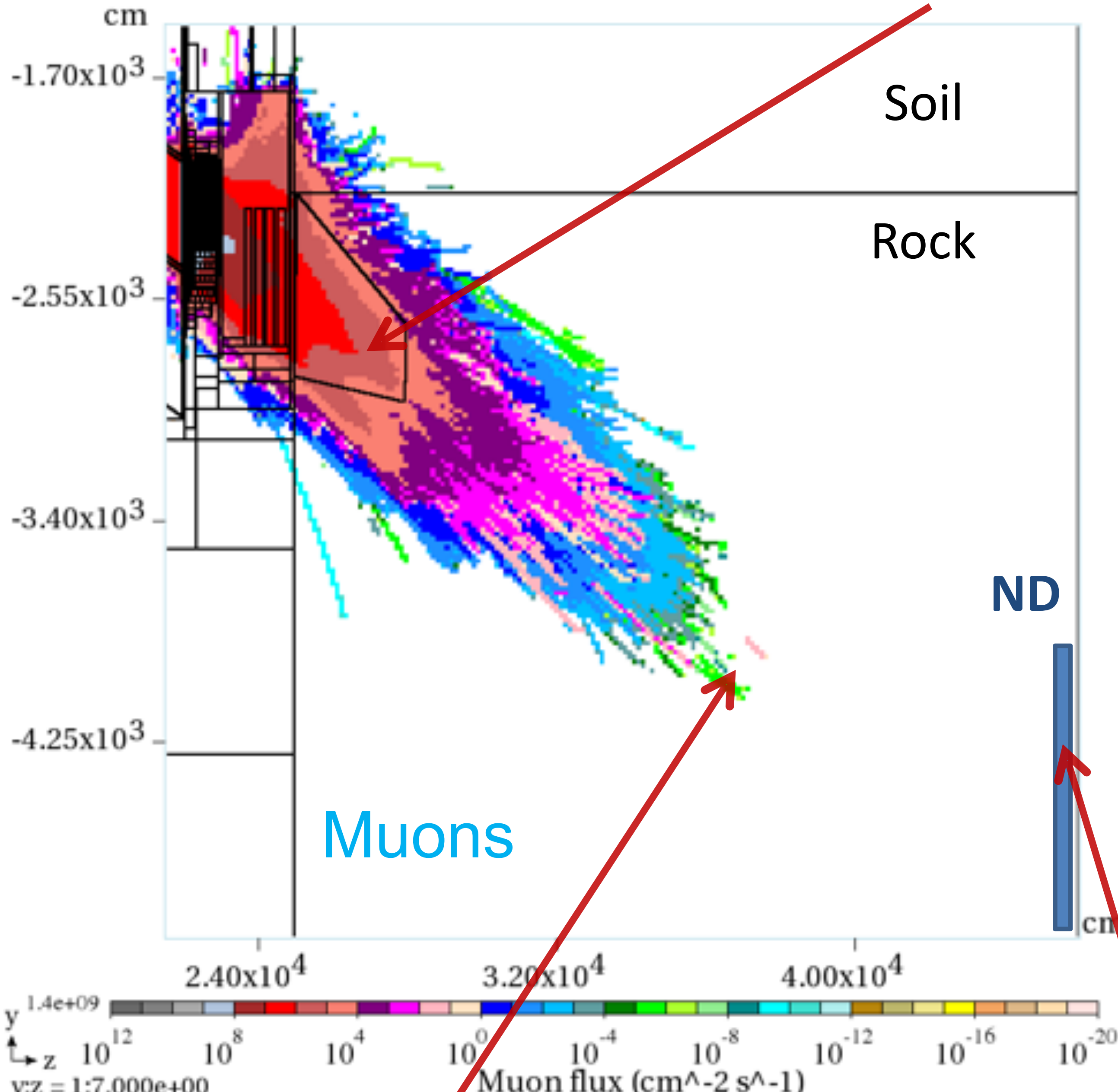
Z=417m, S_{rock}=170 m

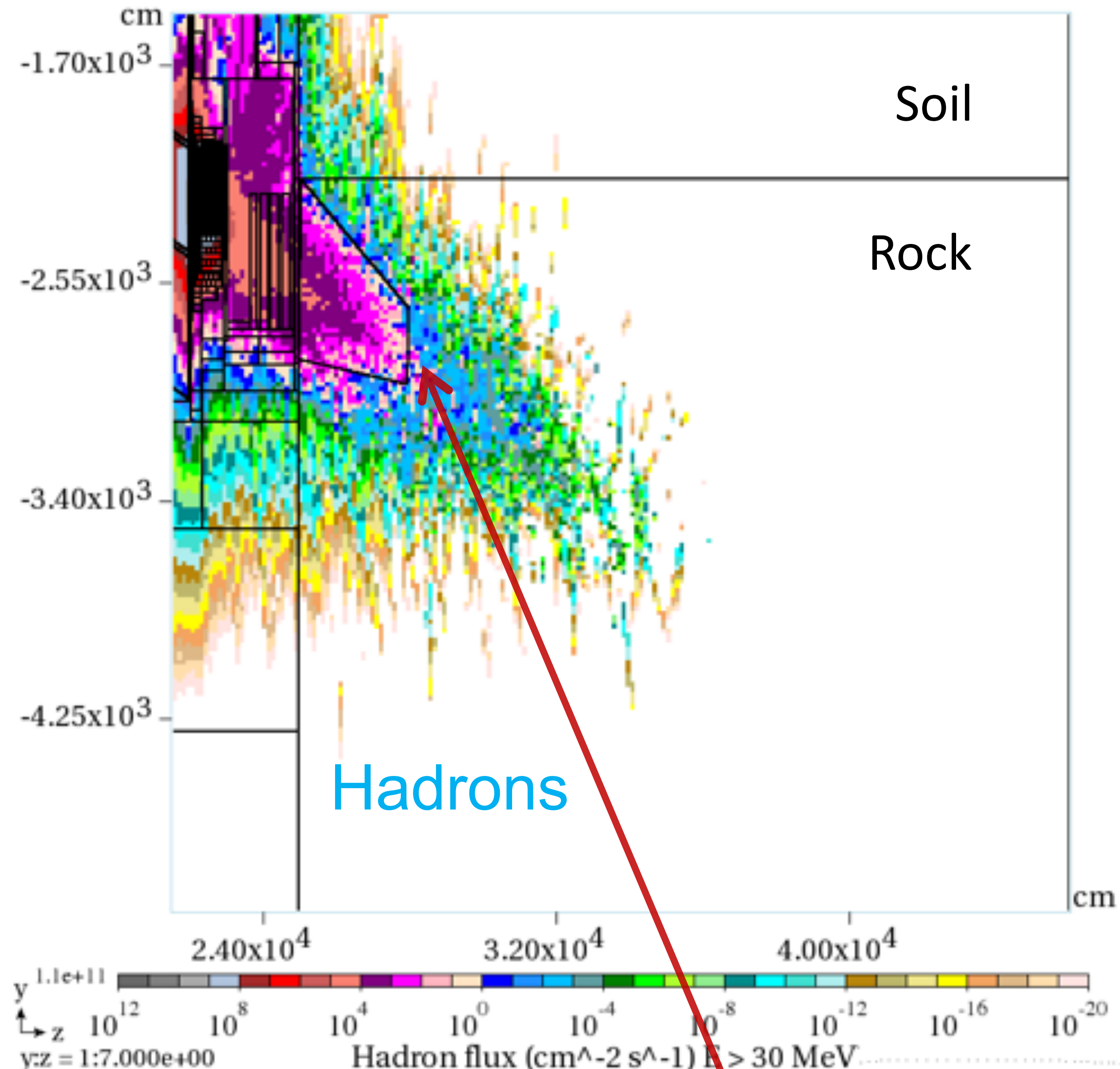
L=459m, Z=456.7 m (previous location of ND)

Z=326.8 m, S_{rock}=80 m Ground-water design goal

Muon/Hadron Fluxes ($cm^{-2}\ s^{-1}$) with Steel Kern. With the muon Kern ND can be placed at z=360 m.

30-m steel kern: R_1=3.5m, R_2=1.5m

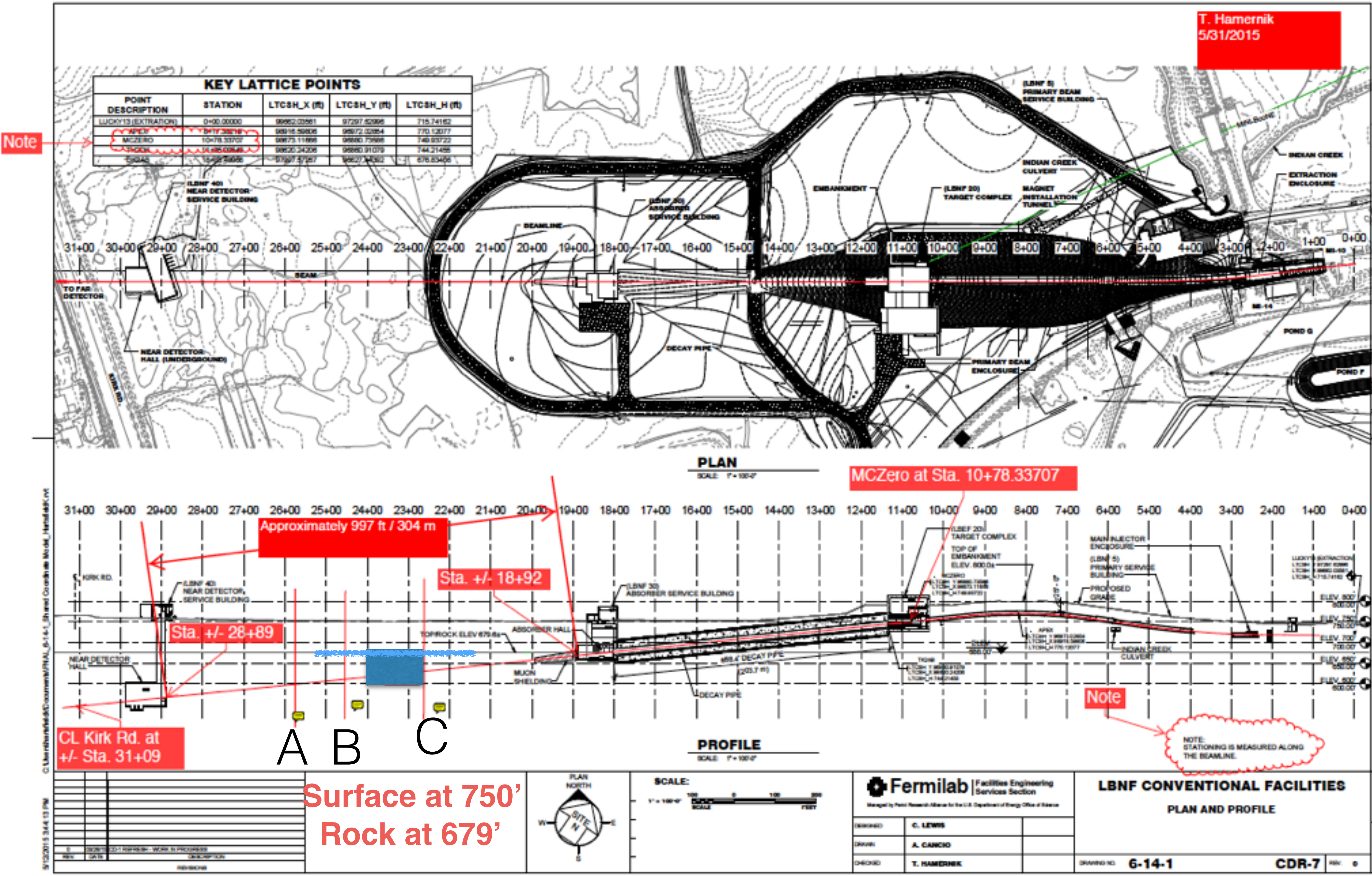




L=459m, Z=456.7 m

Z=360m, S=113 m

Z=277 m, S=30 m
Ground-water design goal

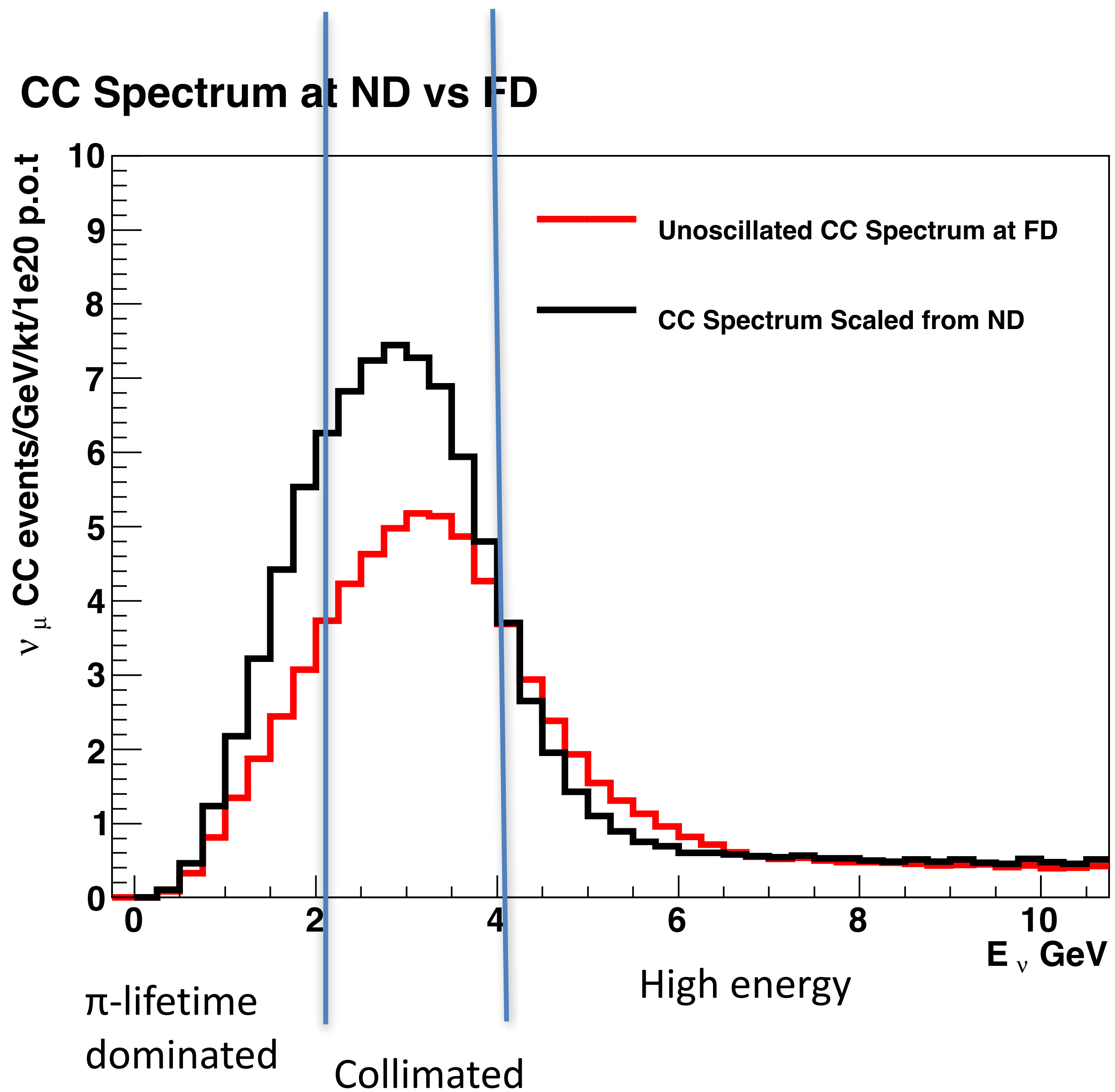


A. previous muon range out (210 m), B. updated (170m), C. with Muon Kern (113 m). Current ND sta. 28+89, Possible nearest location: sta. 22+70. ~(574-188) m = 386 m

Summary 1

- *Two things have changed.*
  - *The muon range distance is much shorter now (113 m).*
  - *We have a much better idea of the ND/FD ratio, how well it can be modeled (~0.5%!)*
- *We should reconsider the near detector distance. There are many scientific and technical advantages.*

ND Neutrino Spectrum



ND at 459 m
120 GeV protons
NuMI horns
ND scaled by $(0.459/1300)^2$

ND rate ~0.1-0.2 evts/ton 7.5×10^{13}

~ 50 % corrections must be made by Monte Carlo. (at 574 the correction is smaller ~40%)

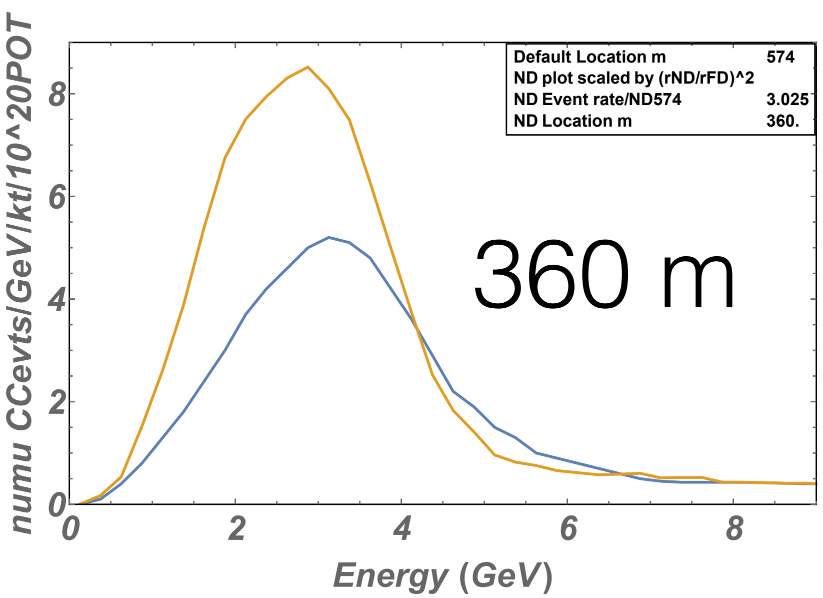
This requires 1) Detailed Beam Geometry Simulation. 2) FD/ND simulations. 3) Reduction of systematics by exploiting correlations.

The apparent average origin of the beam increases upto 4 GeV and then decreases. For the overall beam, the average origin is ~60 meters downstream of target.

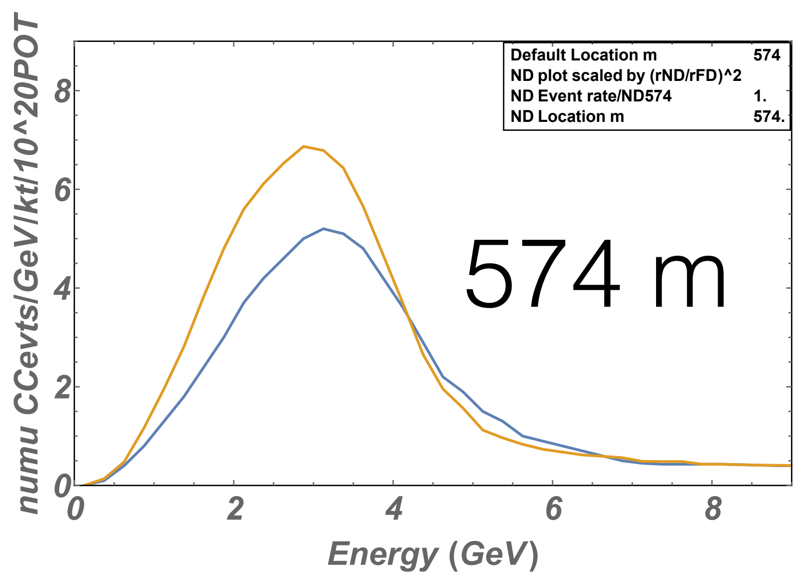
- ND spectrum is narrower than FD due to hadronic distributions, magnetic focusing, decay kinematics.
- NuMI/MINOS technique: data with beam variations can be used to obtain very precise ND/FD ratio.

ND vs FD as a function of ND distance.

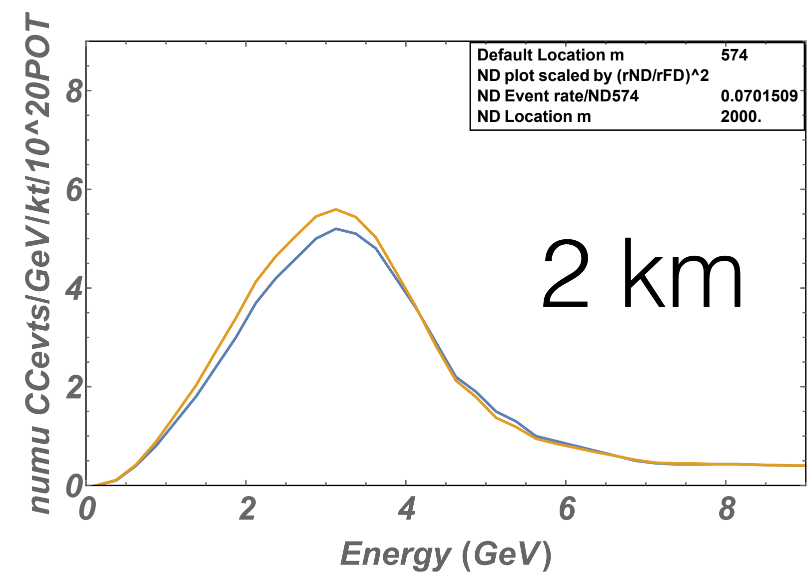
rate = 3.025



rate = 1



rate = 0.07

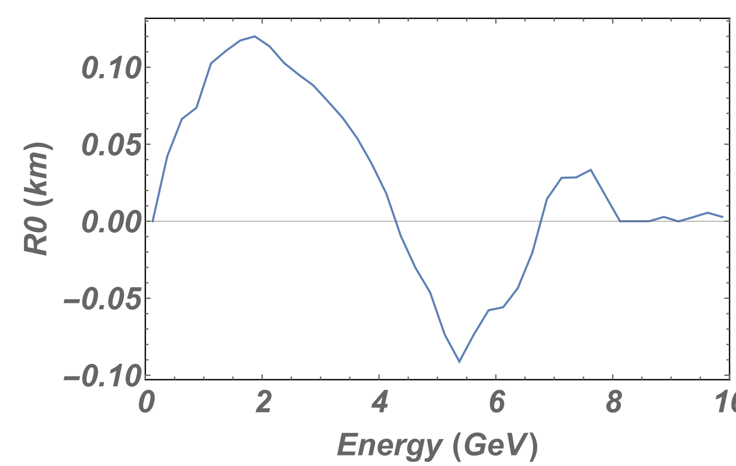


Event rate in ND can be modelled as

$$f(r) \approx \frac{F}{(r - r_0(E))^2}$$

Where r_0 is an energy dependent quantity.

This is good to order $\sim \frac{2\delta r_0^2}{(r - r_0)^2} < 2\%$



This parametrization contains various effects: hadron production, pion/kaon lifetimes, focusing. It can be used to separate the absolute flux and geometry effects to first order.

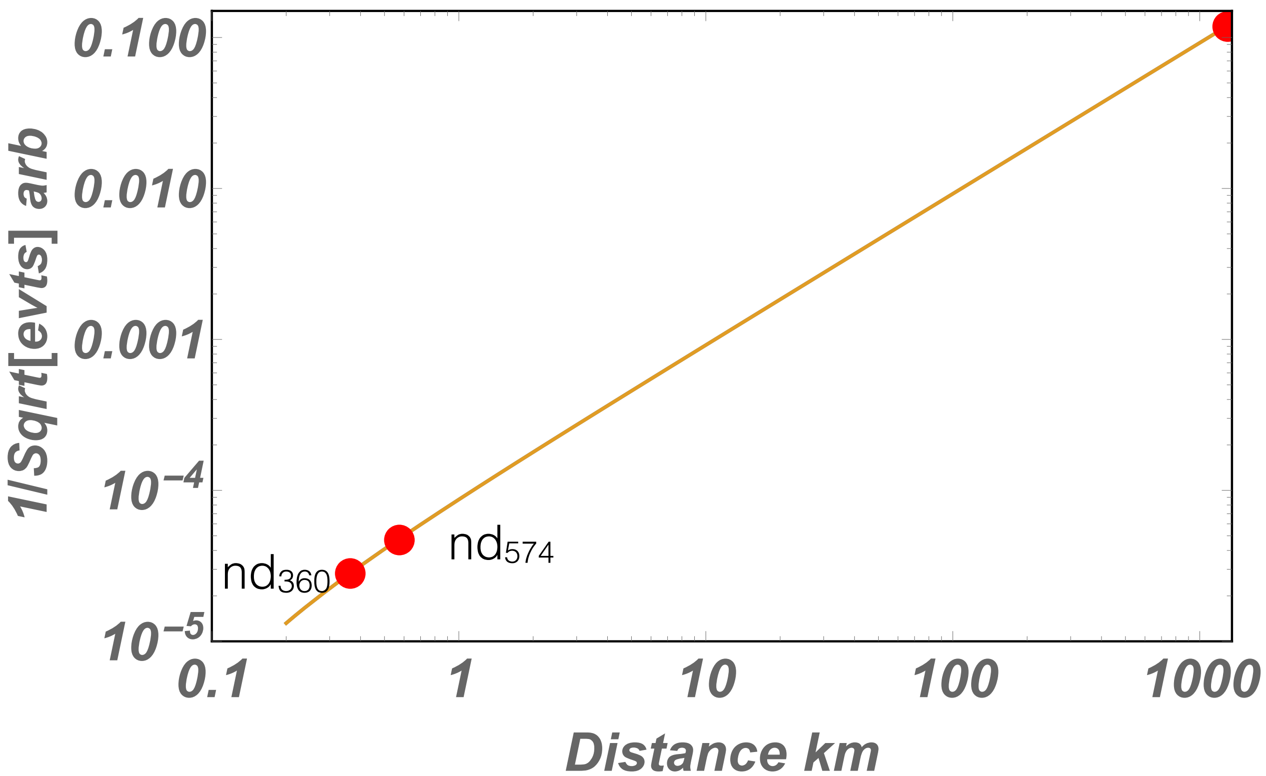
Advantages of ND360

- ***ND360 has factor of 3 higher flux than ND574.***
- ***The flux is extremely important for the key measurement of neutrino electron elastic scattering.***
    - ***nu-e scattering: 5000 events at 574 m, 15000 events at 360 m. (1.2 MW, 5 tons, 5 yrs)***
- ***The spectral distortion at ND574 and ND360 are similar magnitude. There is no clear advantage to ND574 based on flux extrapolation. (it is impractical to consider ND2000).***
- ***ND360 is much shallower. Could allow faster/easier construction.***
- ***Construction could be more favorable for large magnets and equipment.***
- ***If it is found to be necessary for flux extrapolation systematics, it is always possible to construct ND574. (the inverse may not be feasible)***

An analysis model with ND360

- For most precise far detector prediction, use the best known cross section for flux (neutrino-electron elastic scattering).
    - Nu-e scattering should be the yardstick for normalizing all other cross sections and event rates. Therefore nu-e statistics will be the limiting factor for the CP measurement.
    - Measure nu-e scattering in ND360.
- Precise magnetic muon charge measurement will allow separation of neutrino and antineutrino absolute fluxes.
- Use other well known cross sections to check on energy dependence.
- Use Monte Carlo to find FD/ND ratio.
- Use flux measurement and appropriate Ar based detector to obtain cross sections, and detector efficiencies.

Two detector extrapolation



Simple way to understand

$\xi = \dfrac{1}{\sqrt{f(r)}}$ where f(r) is the flux (or event rate) at r

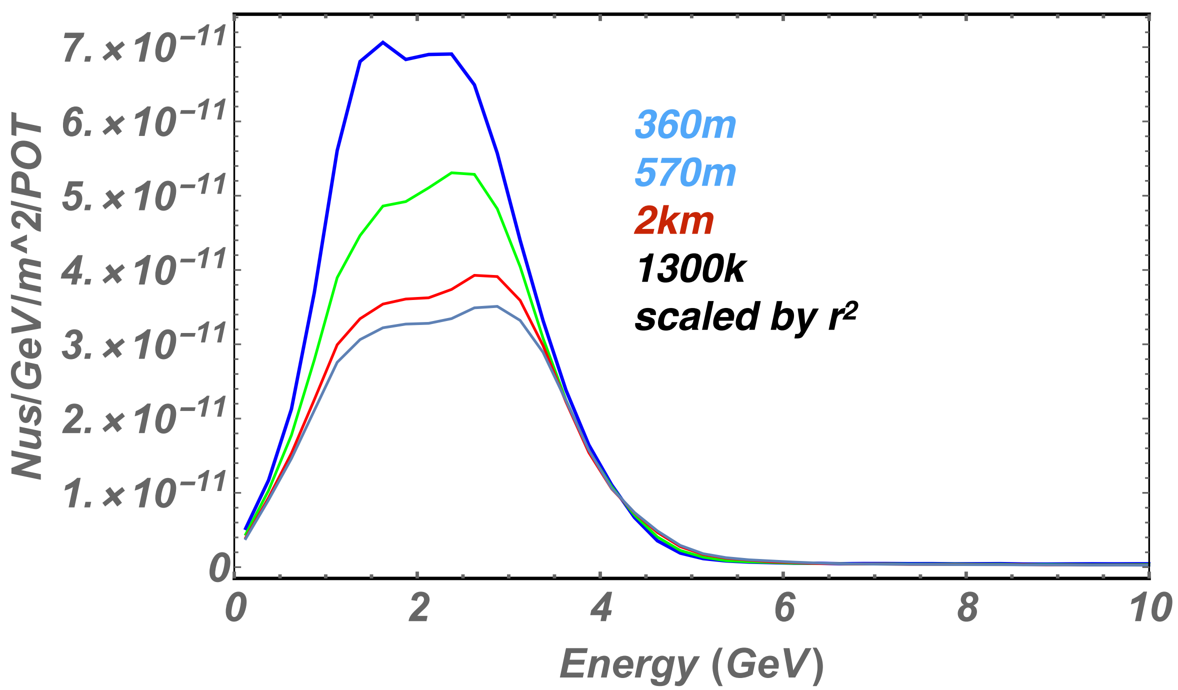
$$\xi(r_3) \approx (\xi(r_1) - \xi(r_2)) \times \frac{r_3}{(r_1 - r_2)}$$

$$\frac{\partial \xi_3}{\xi_3} = \frac{\partial(\xi_1 - \xi_2)}{\xi_1 - \xi_2}$$

proposed in 1995
with an off-axis beam

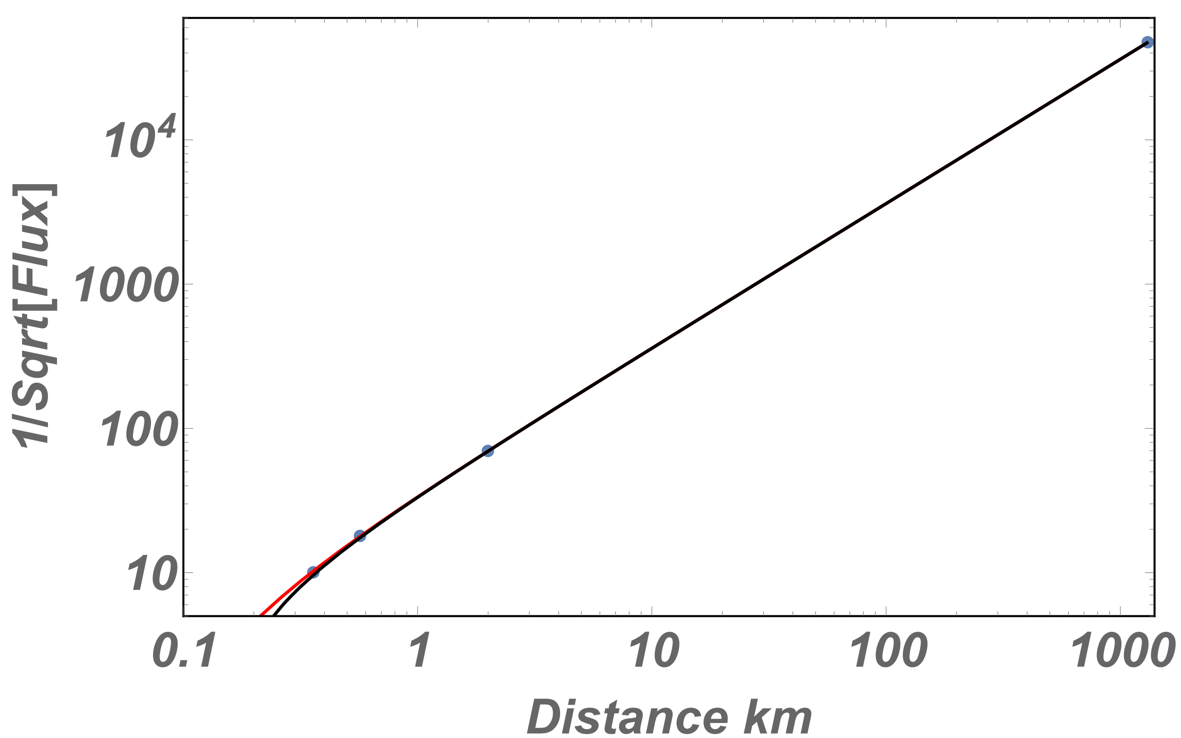
- ***Concern: large extrapolation correction between ND and FD ~ 50-70%. We depend on Monte Carlo to make this correction to ~0.5%***
  - ***The correction is energy dependent and depends on hadron modeling as well as the geometry of the beamline.***
- ***A second ND separated in distance from the first can be used to extrapolate bin by bin and eliminate modeling uncertainties. The second detector (ND574) does not have to be magnetized.***
- ***Precision on the ND360-ND574 extrapolation depends on the error on the event rate difference (including relative efficiencies) between near sites.***

Multidetector extrapolation



From g4LBNE simulation -M. Bishai

Near detector gets relatively more intense as detector comes closer because the apparent origin of the neutrinos is in the tunnel.

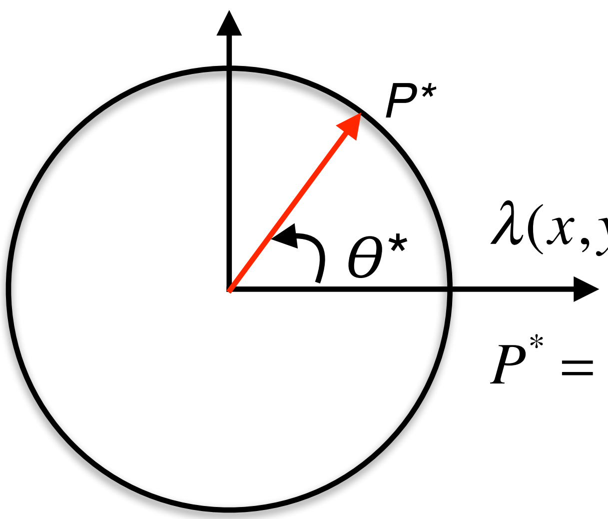


red, black

$$F = 1/(r - r_0)^2$$

$$F2 = 1/(r - r_0)^2 * (1 - \Delta^2/(r - r_0)^2)$$

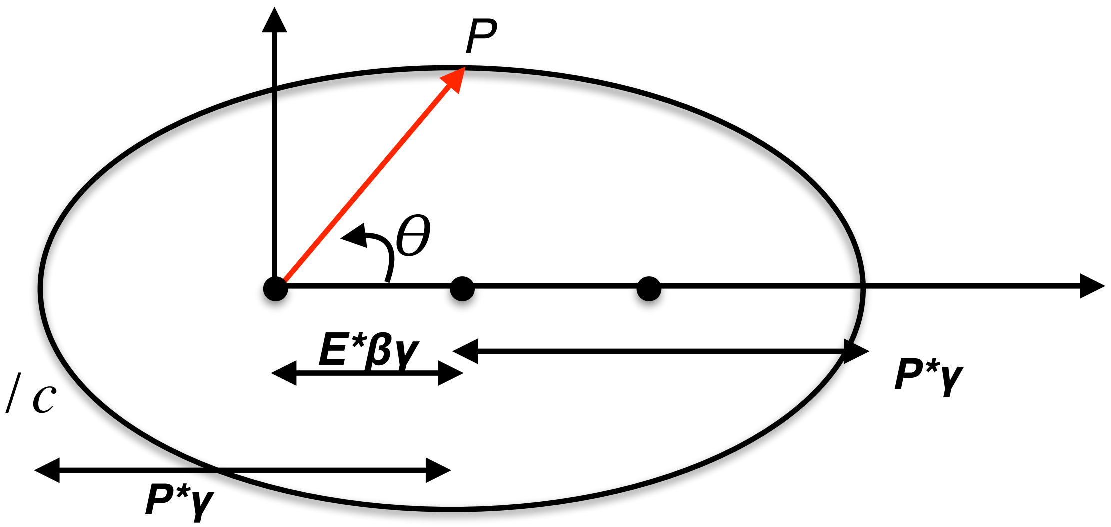
Kinematics of neutrino beam



$$\lambda(x,y,z) = (x-y-z)^2 - 4yz$$

$$P^* = \frac{\lambda^{1/2}(m_\pi^2, m_\mu^2, m_\nu^2)}{2m_\pi} = 29\ MeV/c$$

Boost by γ, β



For a massless particle this is an ellipse with focus at 0

$$P_x = P\sin(\theta) = P^*\sin(\theta^*)$$

$$P_z = P\cos(\theta) = \gamma_\pi P^*\cos(\theta^*) + \beta_\pi\gamma_\pi E^*$$

$$E = \gamma_\pi E^* + \beta_\pi\gamma_\pi P^*\cos(\theta^*)$$

$$E_{\min} = \gamma_\pi E^* - \beta_\pi\gamma_\pi P^*$$

$E_{\max} = \gamma_\pi E^* + \beta_\pi\gamma_\pi P^*$ E is flat between min/max

For the most probable geometry $\theta^* = \pi/2$

$\tan(\theta_C) = \dfrac{P_x}{P_z} = \dfrac{1}{\gamma_\pi}$ for massless particle

$E = \gamma_\pi E^*$ at the most probable θ_C

Example

P_π = 3 GeV
θ_C = 2.65 deg
$P_{\nu M}$ = 0.626 GeV
$E_{\nu MIN}$ = 0.00067 GeV
$E_{\nu MAX}$ = 1.25 GeV

Nu flux from pion decay

$$P_x = P\sin(\theta) = P^* \sin(\theta^*)$$

$$P_z = \gamma_\pi P^* \cos(\theta^*) + \beta_\pi \gamma_\pi E^*; \quad P_z^* = \gamma_\pi P\cos(\theta) - \beta_\pi \gamma_\pi E$$

$$E = \gamma_\pi E^* + \beta_\pi \gamma_\pi P^* \cos(\theta^*); \quad E^* = \gamma_\pi E - \beta_\pi \gamma_\pi P\cos(\theta)$$

$$\tan(\theta) = \frac{\sin(\theta^*)}{\gamma\cos(\theta^*) + \gamma\beta}; \quad \tan(\theta^*) = \frac{\sin(\theta)}{\gamma\cos(\theta) - \gamma\beta}$$

$$\text{Flux in CM frame: } \frac{dN}{d\Omega_{cm}} = \frac{dN}{d\varphi d(\cos\theta^*)} = \frac{1}{4\pi}$$

$$\cos^2\theta^* = \frac{(\cos\theta - \beta)^2}{(\beta\cos\theta - 1)^2} \Rightarrow \frac{d(\cos\theta^*)}{d(\cos\theta)} = \frac{1}{\gamma^2(1-\beta\cos\theta)^2}$$

$$\frac{dN}{d\Omega_{lab}} = \frac{1}{4\pi}\frac{1}{\gamma^2(1-\beta\cos\theta)^2}$$

This is angular distribution.

$$\frac{dN}{dA}(r,\theta) = \frac{1}{4\pi r^2}\frac{1}{\gamma^2(1-\beta\cos\theta)^2}$$

Pion decay spectrum

For proton energy of E_p the pion spectrum is. (assume all are at 0 deg.

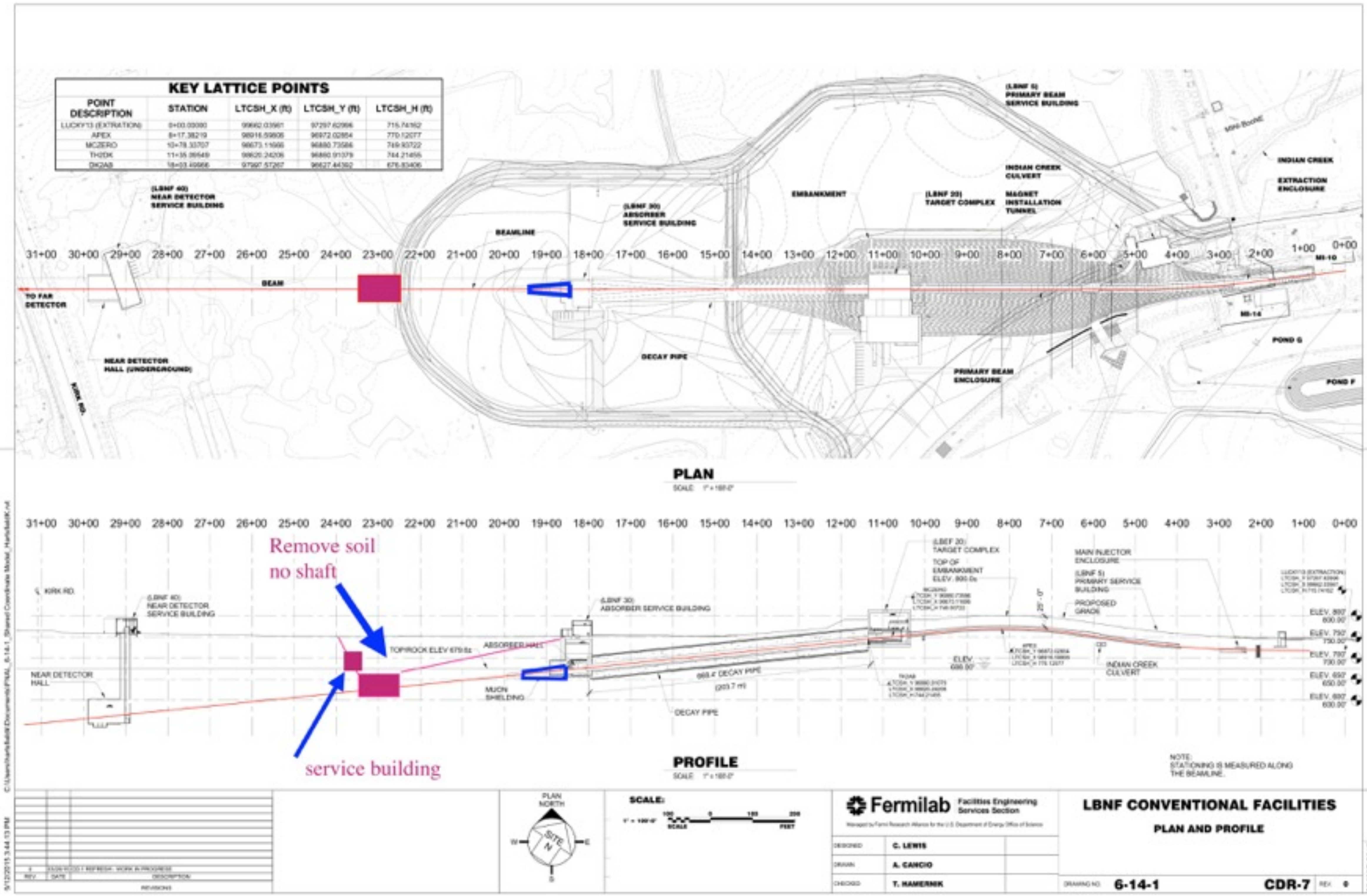
$\frac{dN}{dE_\pi} \approx K \times (E_\pi - E_p)^\alpha$ where K is a constant and $\alpha \approx 5$.

$$\frac{d^2N}{dE_\nu d\Omega_{lab}} = \frac{d^2N}{dE_\pi d\Omega_{cm}} J(E_\pi, \cos\theta^*; E_\nu, \cos\theta)$$

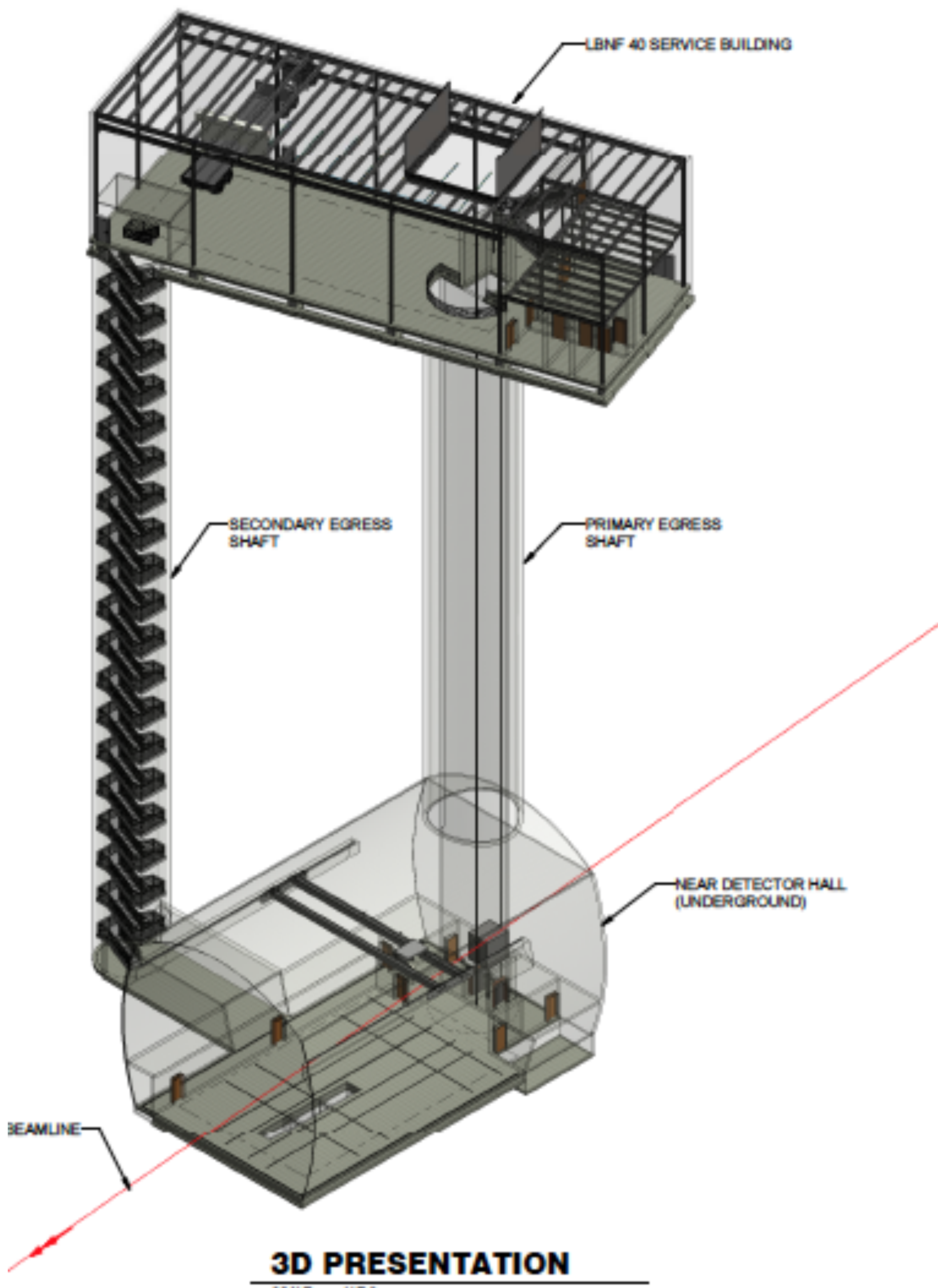
$$J = Det\begin{bmatrix} \frac{\partial E_\pi}{\partial E_\nu} & \frac{\partial \cos\theta^*}{\partial E_\nu} \\ \frac{\partial E_\pi}{\partial \cos\theta} & \frac{\partial \cos\theta^*}{\partial \cos\theta} \end{bmatrix}$$

We will do this calculation later. It can be used to construct the moments for the beam.

Near reconfiguration



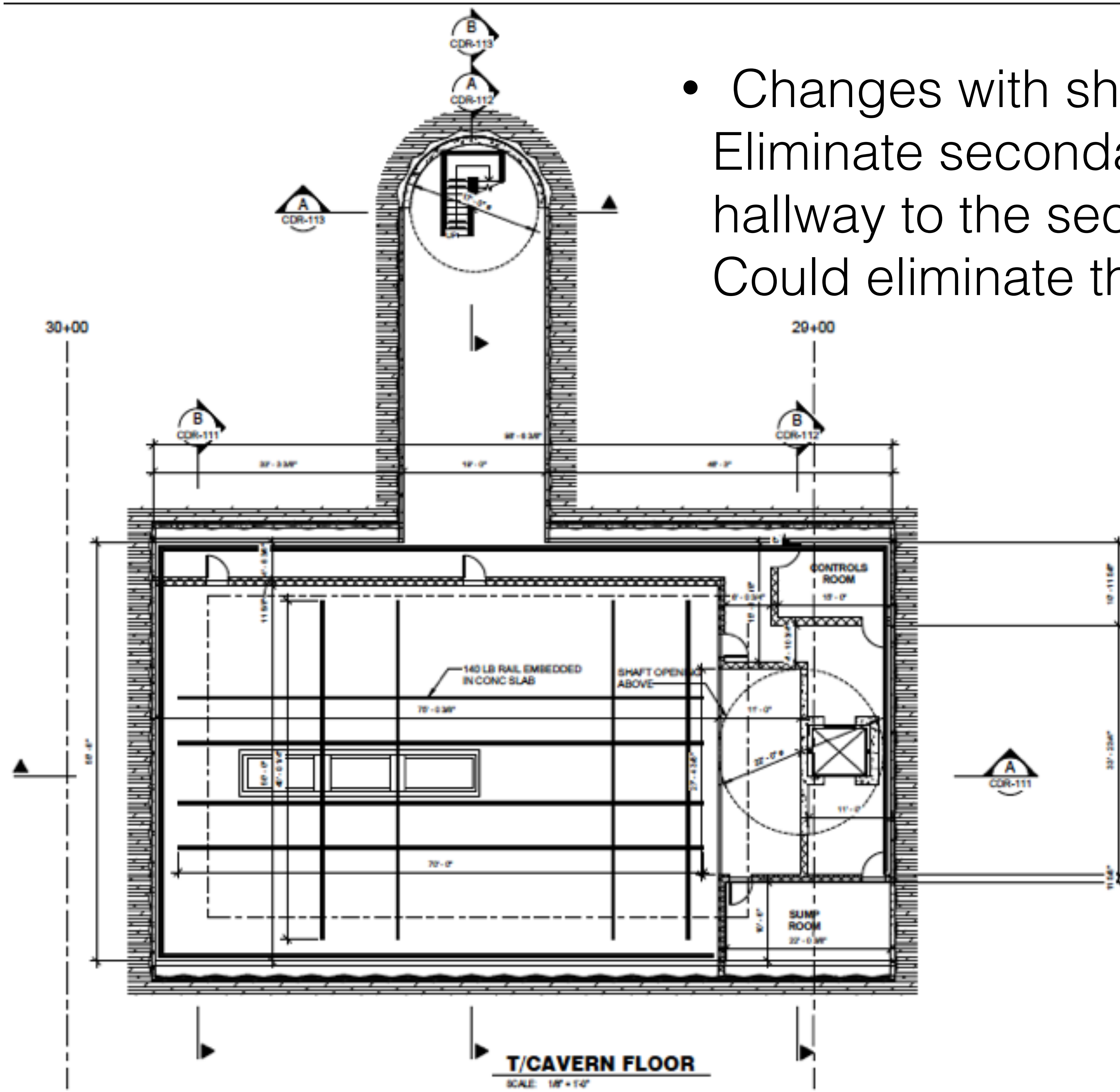
ND hall in 3d



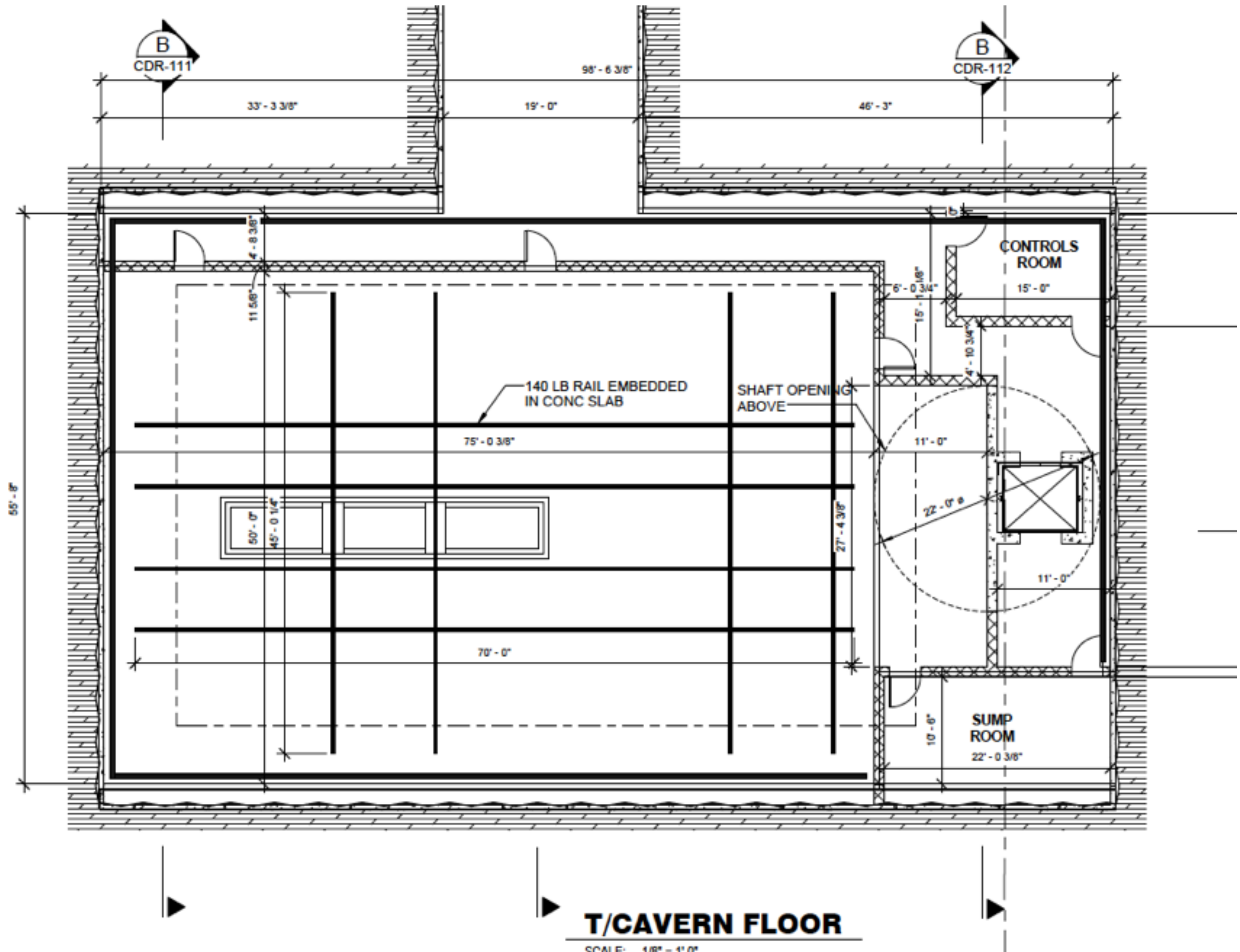
In a shallow excavation both secondary egress and the service building could be eliminated.

Current underground ND cave

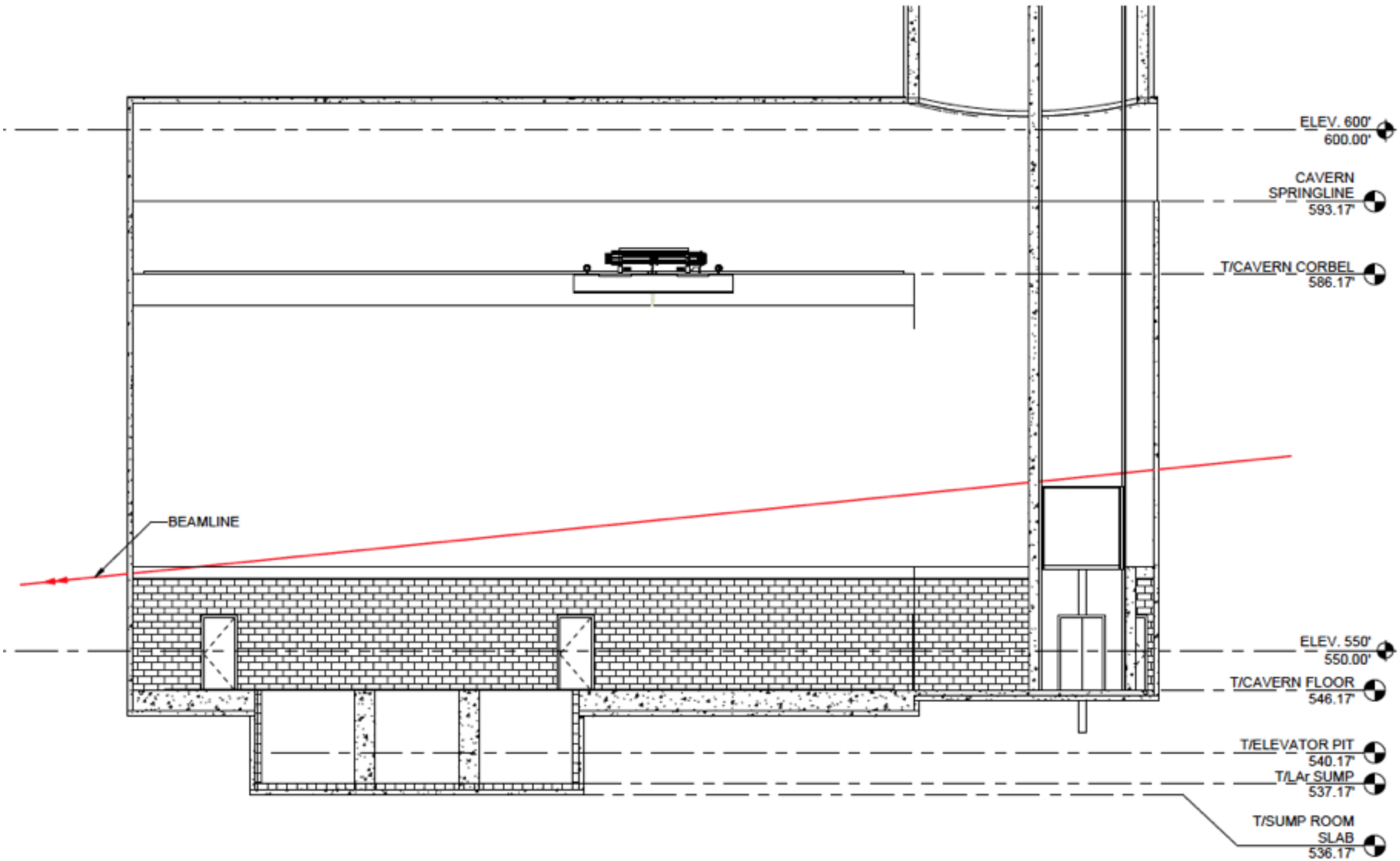
- Changes with shallow location - Eliminate secondary egress and the hallway to the secondary egress. Could eliminate the controls room.

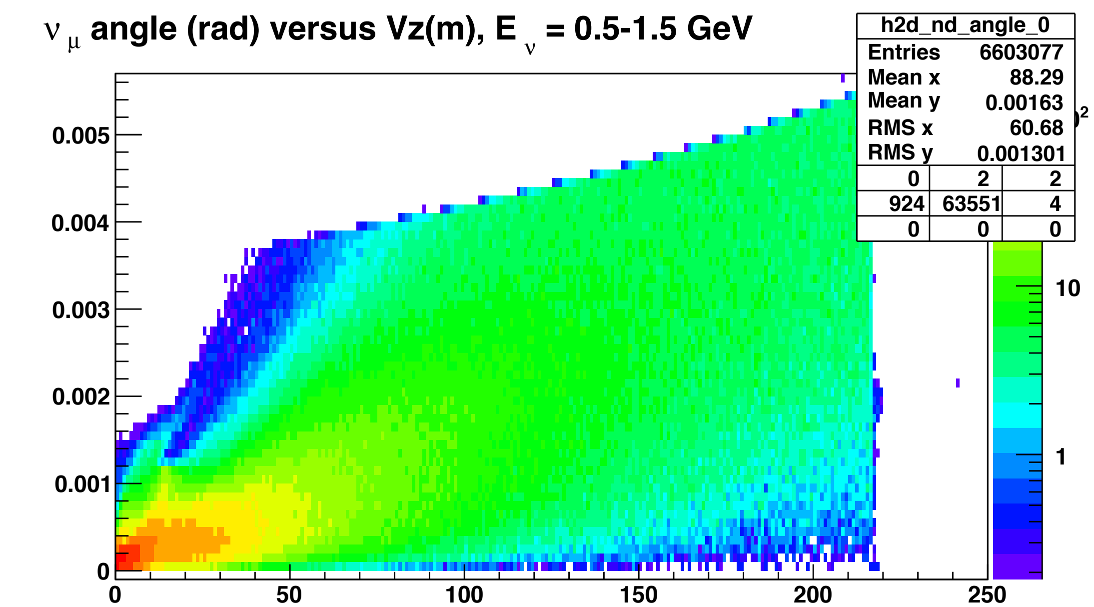


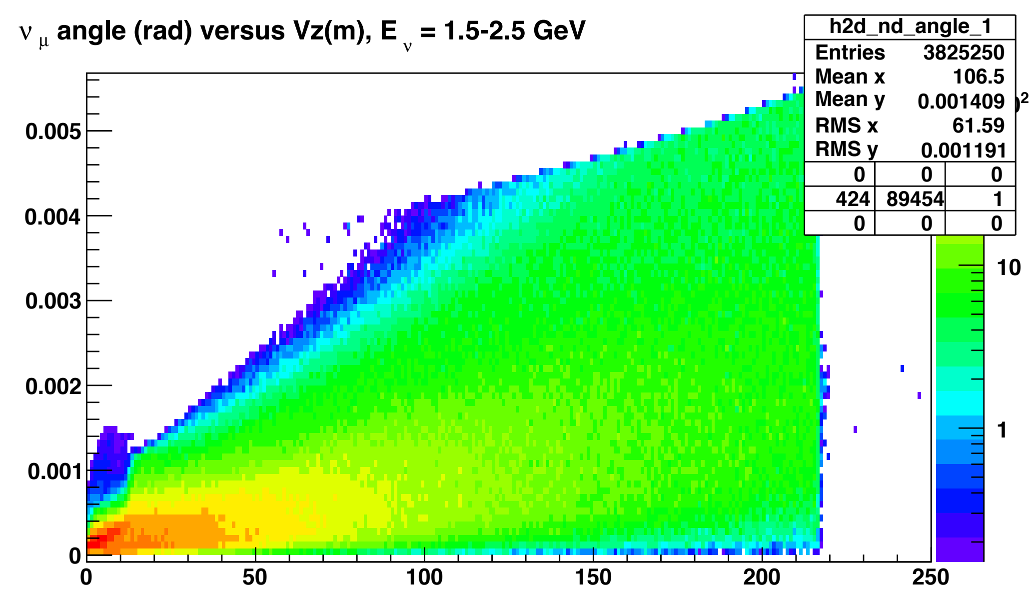
ND space plan view

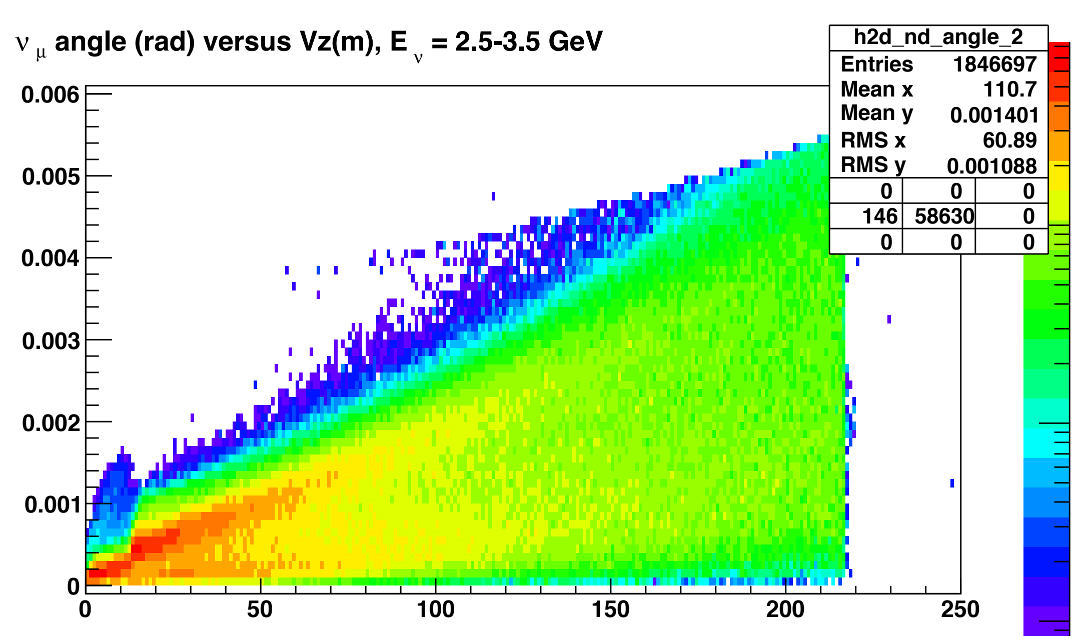


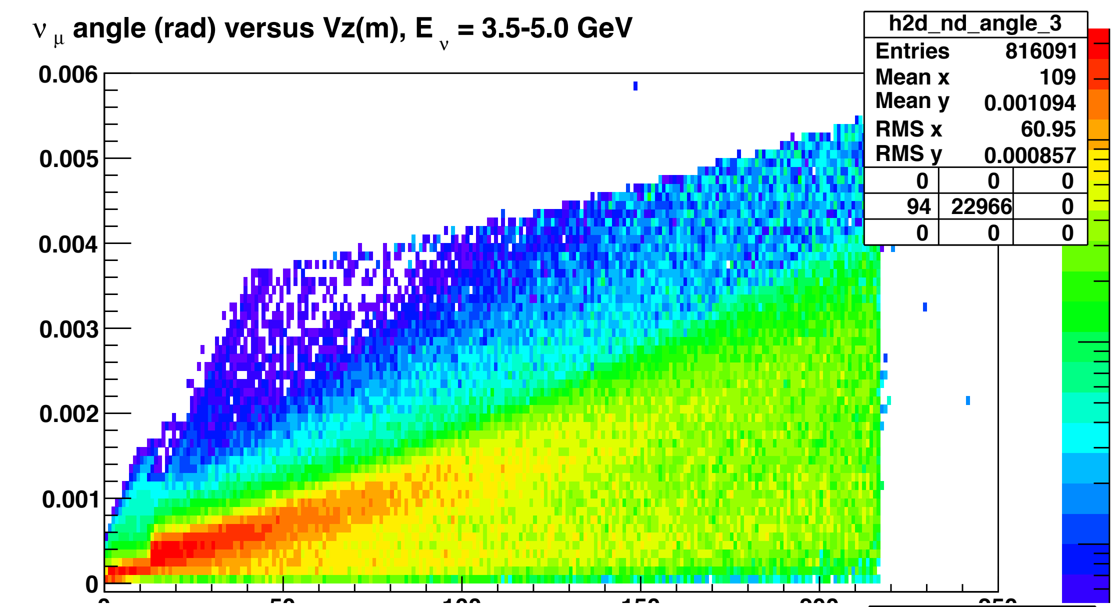
ND elevation view

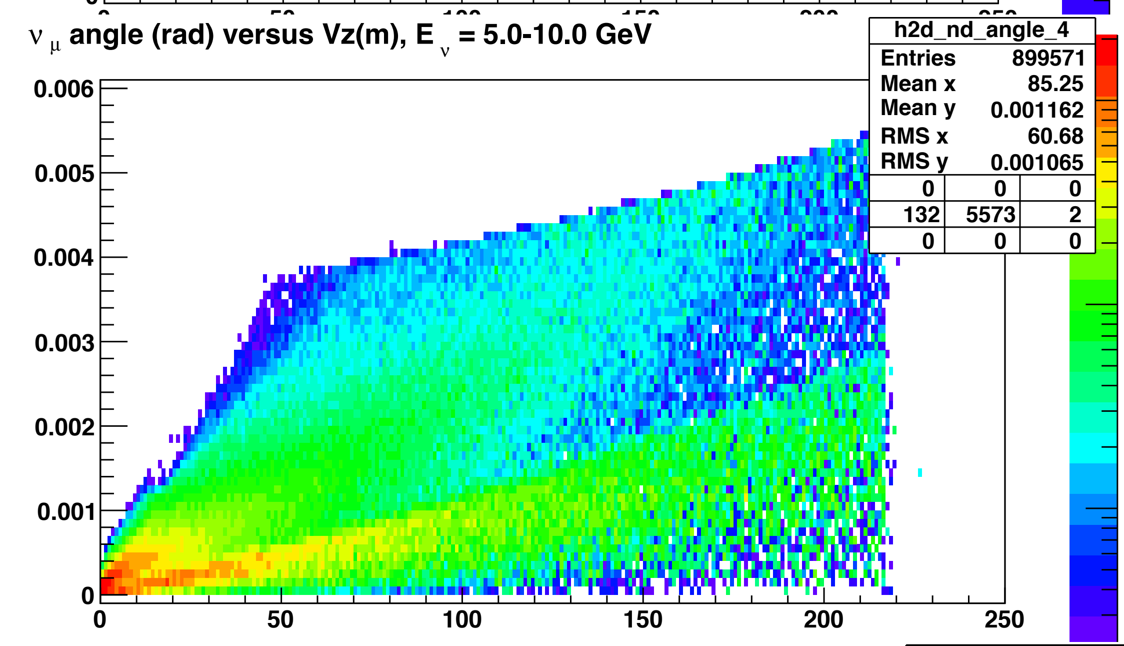


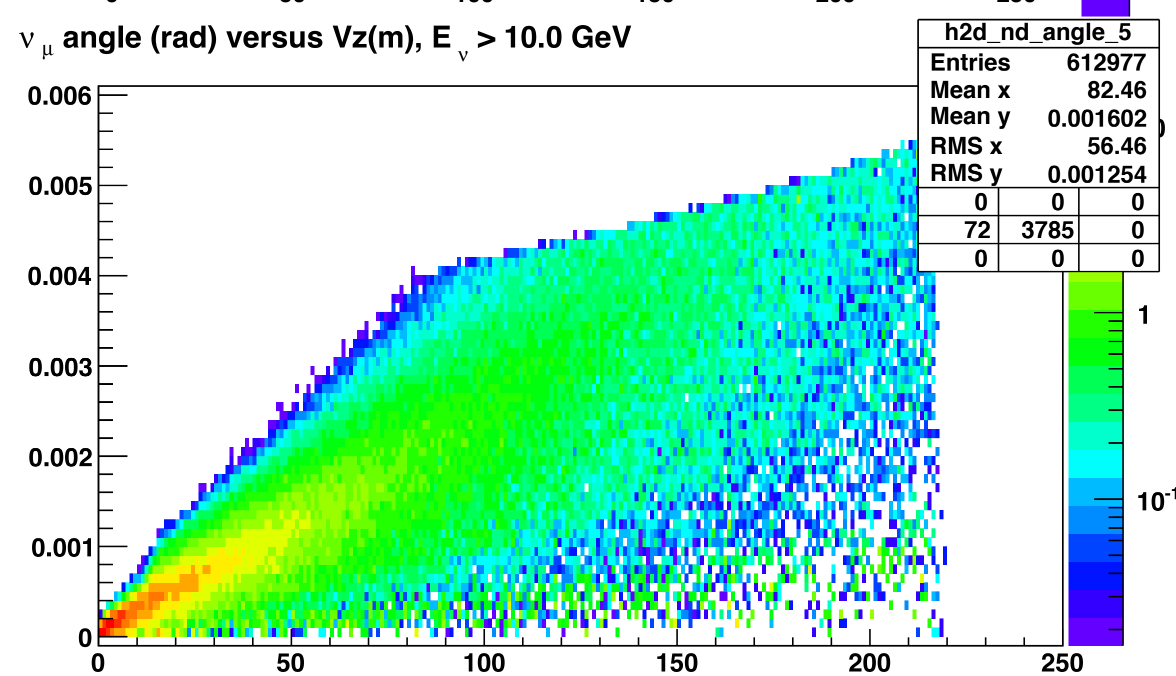

ν μ angle (rad) versus Vz(m), E ν = 0.5-1.5 GeV
h2d_nd_angle_0
Entries 6603077
Mean x 88.29
Mean y 0.00163
RMS x 60.68
RMS y 0.001301
0 2 2
924 63551 4
0 0 0

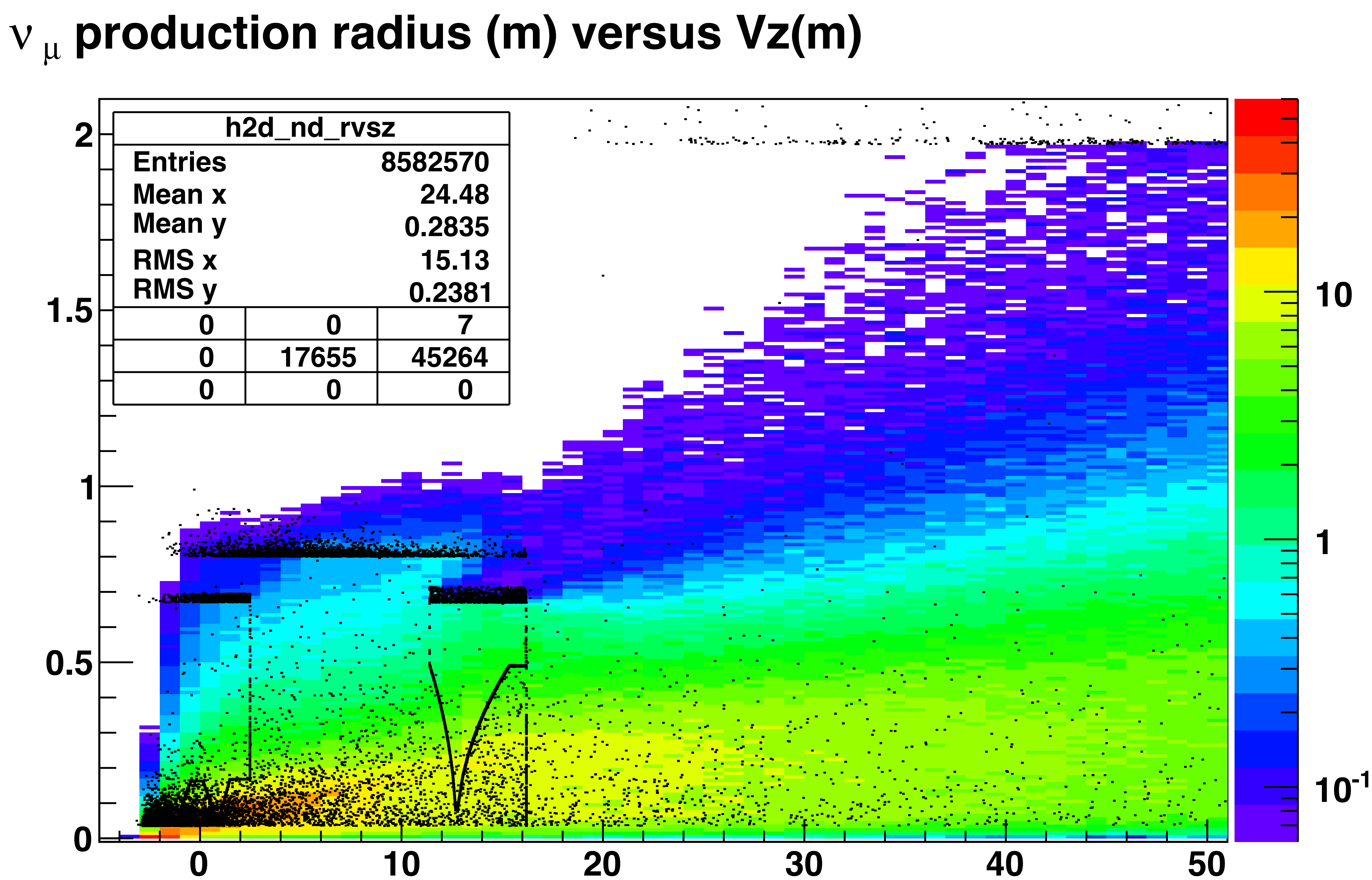

ν μ angle (rad) versus Vz(m), E ν = 1.5-2.5 GeV
h2d_nd_angle_1
Entries 3825250
Mean x 106.5
Mean y 0.001409
RMS x 61.59
RMS y 0.001191
0 0 0
424 89454 1
0 0 0


ν μ angle (rad) versus Vz(m), E ν = 2.5-3.5 GeV
h2d_nd_angle_2
Entries 1846697
Mean x 110.7
Mean y 0.001401
RMS x 60.89
RMS y 0.001088
0 0 0
146 58630 0
0 0 0


ν μ angle (rad) versus Vz(m), E ν = 3.5-5.0 GeV
h2d_nd_angle_3
Entries 816091
Mean x 109
Mean y 0.001094
RMS x 60.95
RMS y 0.000857
0 0 0
94 22966 0
0 0 0

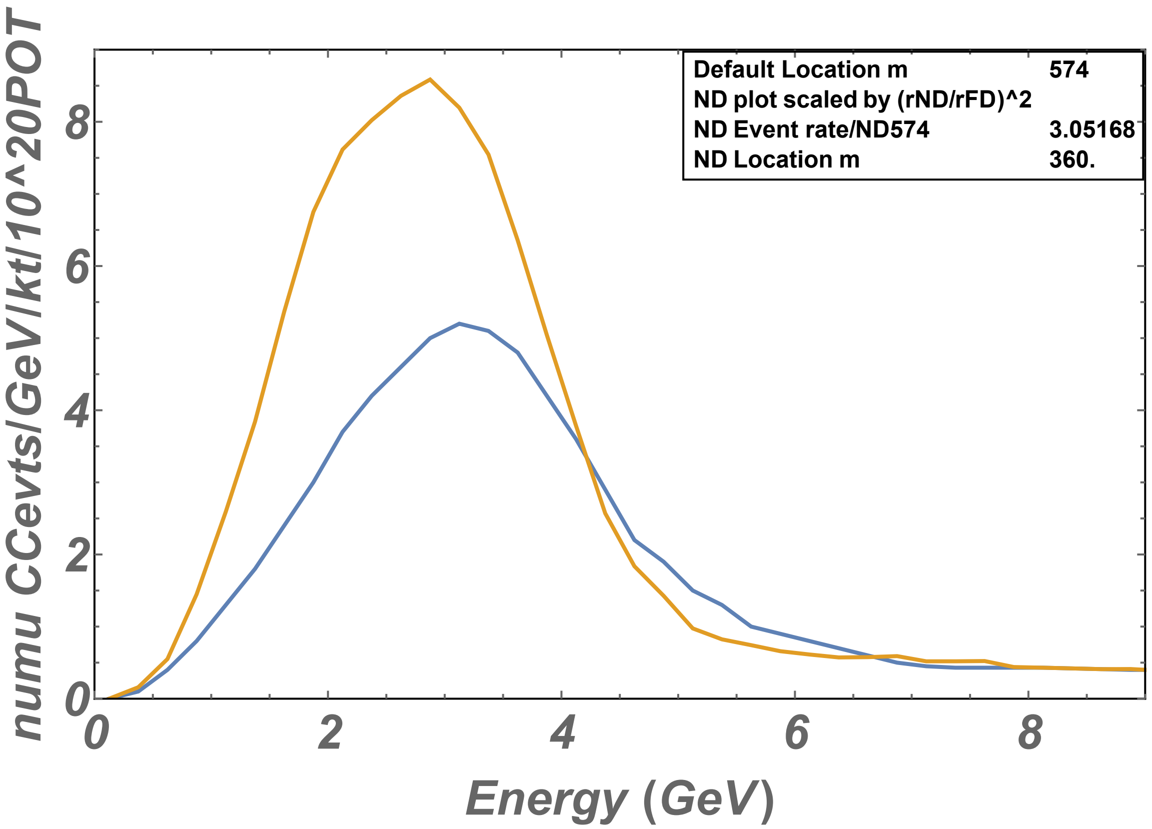

ν μ angle (rad) versus Vz(m), E ν = 5.0-10.0 GeV
h2d_nd_angle_4
Entries 899571
Mean x 85.25
Mean y 0.001162
RMS x 60.68
RMS y 0.001065
0 0 0
132 5573 2
0 0 0

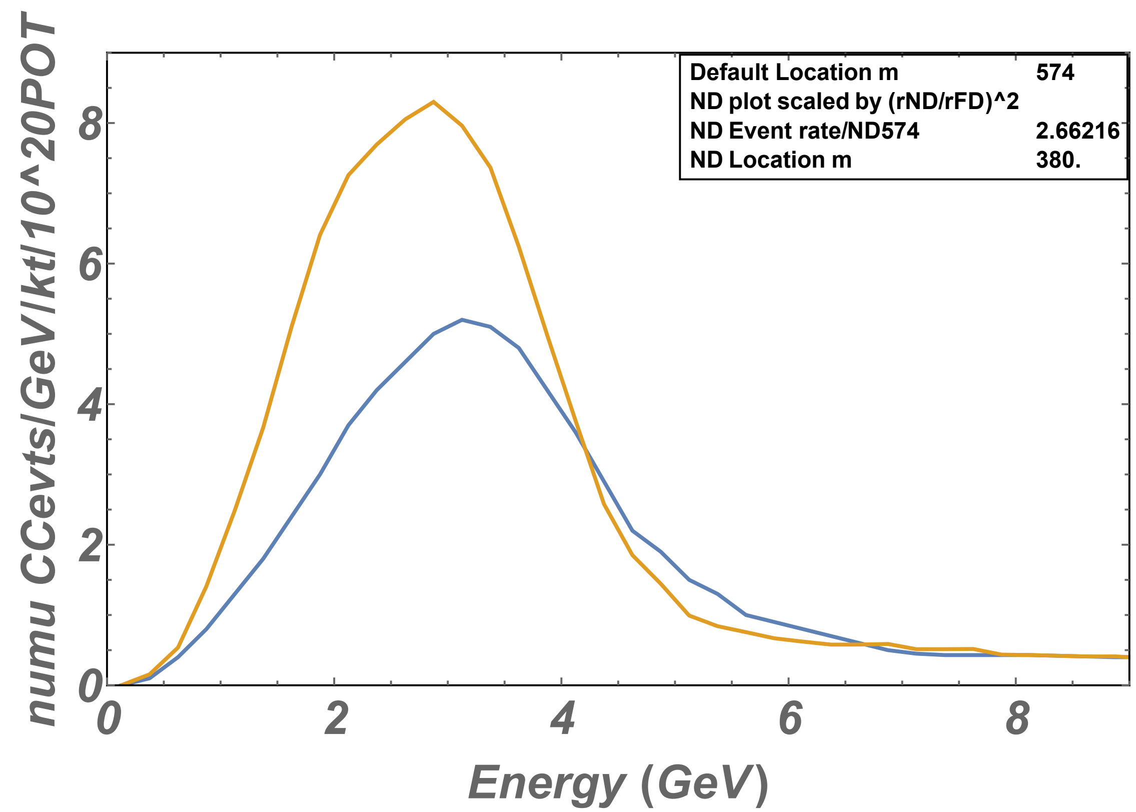

ν μ angle (rad) versus Vz(m), E ν > 10.0 GeV
h2d_nd_angle_5
Entries 612977
Mean x 82.46
Mean y 0.001602
RMS x 56.46
RMS y 0.001254
0 0 0
72 3785 0
0 0 0

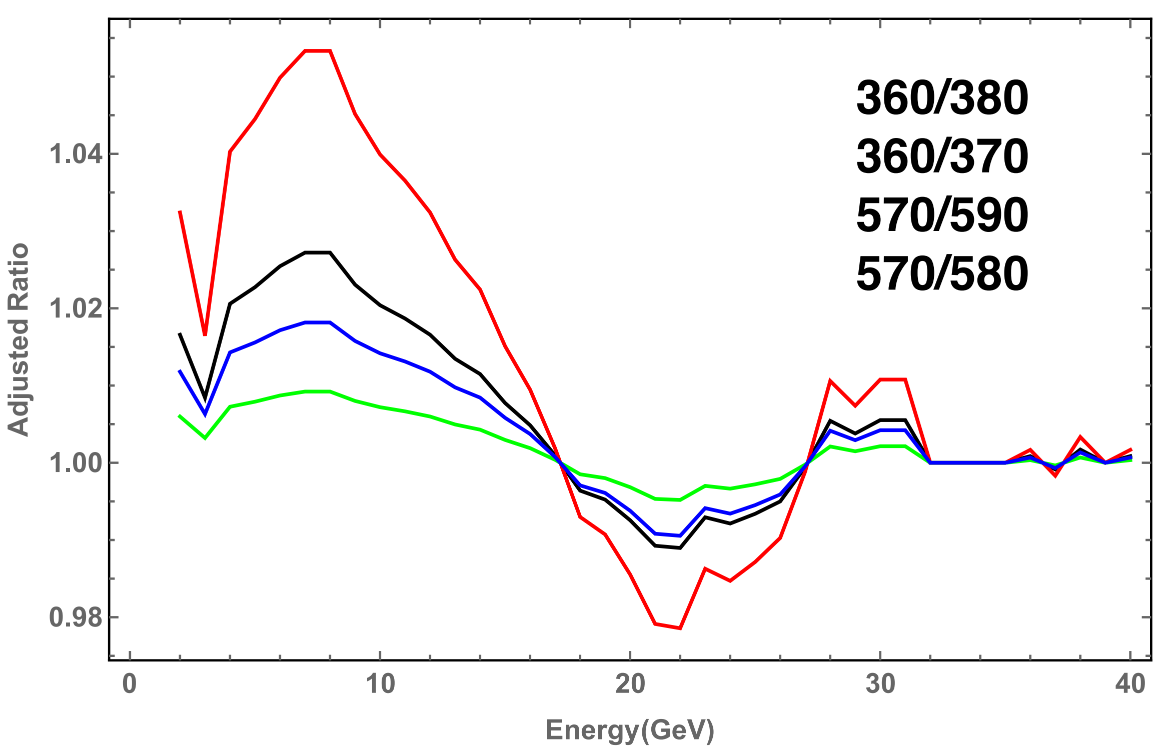

ν_μ production radius (m) versus Vz(m)
h2d_nd_rvsz
Entries 8582570
Mean x 24.48
Mean y 0.2835
RMS x 15.13
RMS y 0.2381
0 0 7
0 17655 45264
0 0 0
2
1.5
1
0.5
0
0
10
20
30
40
50
10
1
10^{-1}

Observations

- The distribution of neutrino directions and origins determines the beam divergence and flux extrapolation.
- The neutrino angles in the near detector range from < 1 mrad to ~ 5 mrad as a function of decay distance from the target.
- Measurement of neutrino angle could be done with nu-electron elastic scattering if the detector is made low density. => tracking with radiation length ~0.5%. (0.7 mm of Lar).
- A long detector at 360 m will allow measurement of the divergence. Is this possible ?

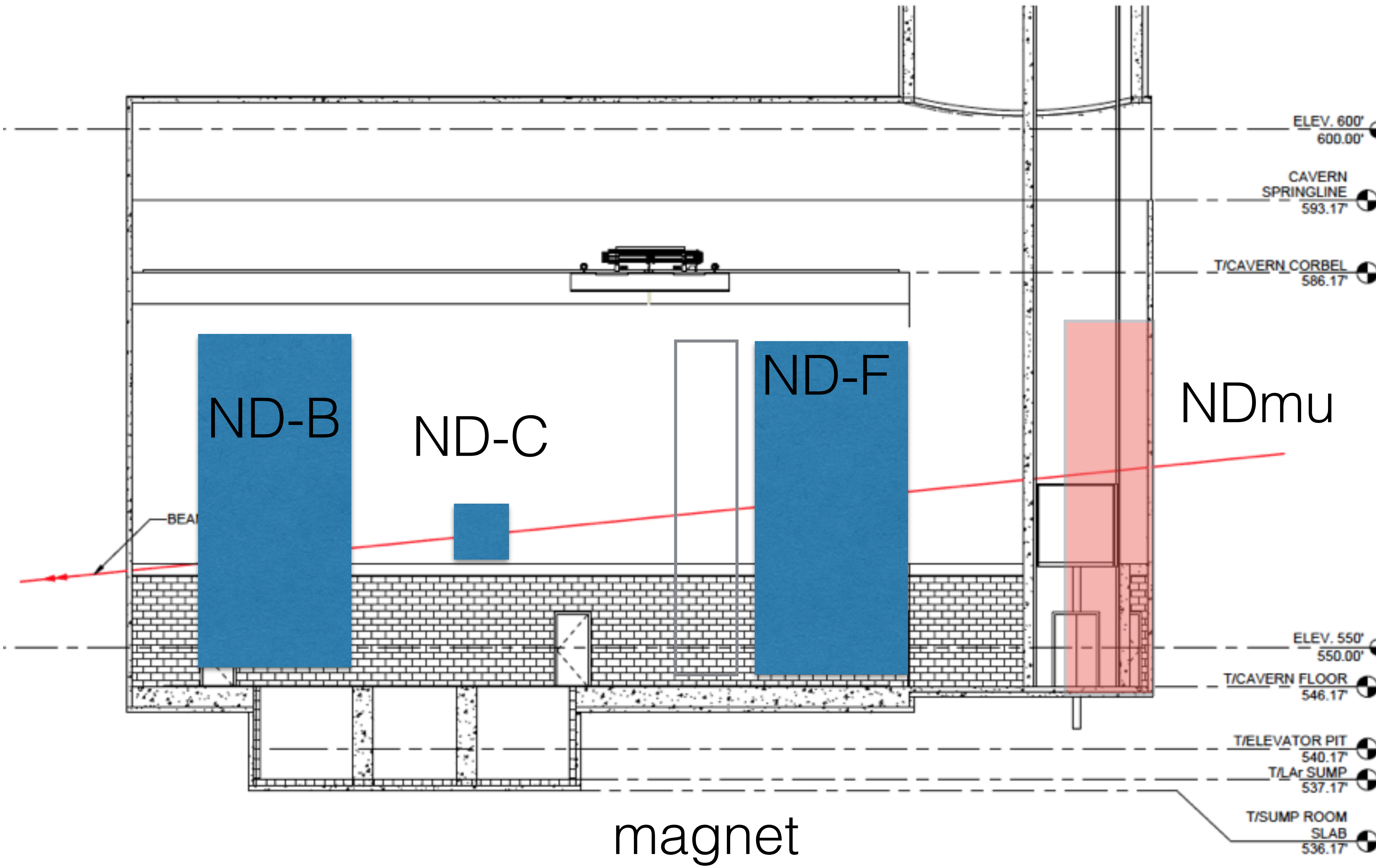






- **Flux falls by ~15% over 20 meters at 370 m.**
- **The shape changes by ~8% over 20 meters.**
- **if we can measure this precisely**
  - **Perform extrapolation to FD**
  - **Calculate the electron neutrino flux in the beam precisely.**

ND elevation view



ND-Front, ND-back may require making the hall longer, but current dimension of 21 m may be adequate.